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Editorial Comment

MORE OPTICS MEANS LARGER JOURNALS

THE present international emergency has caused no decrease in the publication in America of the results of optical research, but thus far has marked an increase. Volume 31 of this Journal, which the present issue now brings to completion, bulks larger than any of its predecessors. As recently as 1937 the Journal contained only 428 pages—for the year now closing the corresponding figure is 776, an increase of 81 percent. Yet for this larger Journal subscribers continue to pay $6 per year, associate members of the Optical Society $5, and regular members $7.50. Since the Journal has never made a profit for the Society, one may well wonder how it could be nearly doubled in size without incurring a serious deficit.

A Journal so large, furnished to the subscription list of even two years ago, would cost the Society about $10 per subscriber. Since it is the duty of the Board of Directors to avoid incurring an annual deficit that would imperil the financial position of the Society, it is obvious that the Journal would be forced under these circumstances to cut down its size, raise its subscription price to $10 or over, or find some alternative. The most attractive alternative is to increase the number of subscribers until the cost per subscriber, reduced by wider spreading of overhead costs, comes down to the actual amount paid for the subscription.

The calculated balance point for 776 pages turns out to be a number of subscribers equal to about twice the number receiving the Journal in 1937. Fortunately the larger Journal has attracted more readers, and the past two years have seen a growth in circulation approaching 50 percent. However, to reach the balance point for a Journal of the present size, about 350 new subscribers and 350 new associate members of the Society are needed.

The $3 charged to authors or sponsors by all American physics journals for each page published represents only a small fraction of the actual cost of publication. To pay for a single additional page in one issue of the Journal, at least 36 extra copies of that issue, or the equivalent, must be sold.

If you now subscribe to the Journal you are accepting a gift from the Society of more than two dollars per year. The easiest way to eliminate the need for this gift is to persuade some friend who needs the Journal to subscribe for it or join the Optical Society—if this is done your two subscriptions together may be thought of as paying their own way in full. In the past, several members have been responsible for bringing into the Society more than a hundred members each. If each present member could do even 1 percent as well the Society could support a Journal even larger than the present one, thus improving a channel of scientific publication that is ever more important in a world where so many such channels are being closed.

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A General Law of Diminution of Light Intensity in Natural Waters and the Percent of Diffuse Light at Different Depths*

LESTER V. WHITNEY
State Teachers College, Springfield, Missouri
(Received August 27, 1941)

INTRODUCTION

VECTOR diagrams of the angular distribution of light intensity measured at different depths suggest a modification of the simple exponential law, $I_z = I_0 e^{-kz}$, when applied to light which penetrates natural waters. The purpose of this article is to develop a general law of diminution of light intensity and to express the percent of scattered light directed downward as a function of depth.

Before discussing a derivation of a general diminution law it is necessary to review briefly some well-known experimental facts concerning the penetration of light into natural waters. It is quite customary to take into account the direction of solar rays when the extinction coefficient is determined by experimental measurements of light intensities at different depths in a lake or in the ocean. For example, if the sun were 60° from the zenith the refracted rays under water would make an angle of about 41° with the zenith and solar radiation would travel 133 centimeters to reach a depth of 1 meter. (In what follows, this distance, 133 centimeters, would also be defined as the mean path length under conditions of 60° sun and zero percent sky radiation.) If under these conditions the experimental measurement of transmission were 62 percent, or, if the light intensity at one depth were 62 percent of that 1 meter above, the transmission corrected for zenith sun would figure 70 percent per meter and the extinction coefficient in the exponential law 0.495. However, since the sky had been neglected, this result would only be approximate. It is somewhat tedious to allow for the radiation from all parts of the sky even though the sky itself be assumed of uniform brightness. The several factors which must be considered, the area of each elemental sky zone at a particular angle from the zenith, the Fresnel reflection coefficient at the water surface, the extinction coefficient of the water, and the different path lengths of each portion of the radiation in traveling to a depth of 1 meter, all combine to give an integral too complicated for ordinary solution. Graphical methods may be employed or the sky may be broken down into a finite number of zones. The author found the latter method convenient and sufficiently accurate. The method is outlined in an article on solar radiation measurements in Wisconsin lakes.[1] In brief, the solution may be approximated by assigning a mean path length for each combination of sun angle and percent of sky energy. The mean path length is defined as that average distance which a single beam of light could travel and be reduced by the same percent as is the actual total sun and sky radiation in reaching a depth of 1 meter. If, in the preceding illustration, the

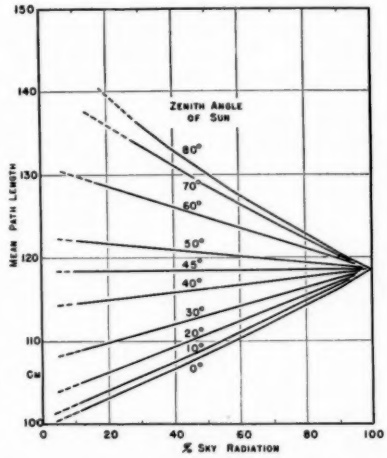

FIG. 1. Mean path lengths for total direct radiation for various zenith sun angles and various percentages of sky radiation. Dotted portions of lines indicate conditions never met with experimentally.

* From the Limnological Laboratory of the Wisconsin Geological and Natural History Survey. Notes and reports No. 92. This investigation was supported by a grant from the Brittingham Trust Fund.

[1] L. V. Whitney, "Continuous solar radiation measurements in Wisconsin Lakes," Trans. Wis. Acad. Sci. Art. and Let. **31**, 175–200 (1938).

amount of sky energy as recorded by a flat horizontal receiver had been 40 percent of the total sun and sky energy, the mean path length would be 126 centimeters instead of 133. In other words, the 62 percent transmission as experimentally determined should be associated with a distance of 126 centimeters instead of 133. The resulting transmission, corrected for all light from the zenith, would calculate 68.5 percent and the extinction coefficient 0.505. Figure 1 shows mean path lengths as a function of zenith sun angle and percent sky radiation. It may be noted that the mean path length of a uniformly clouded sky, or 100 percent sky radiation, is a little over 118 cm. This agrees with values calculated by other experimenters.

If corrections of this sort were not applied it is apparent that the extinction coefficient determined experimentally in natural waters would be meaningless. In the upper water at least, it would vary with the angle of the sun and the percent sky energy instead of depending only on the optical properties of the water itself. But there is reason to believe that even if all light came from the zenith, a condition similar to laboratory conditions when a parallel beam is sent through a tube, a similar correction should be applied as light penetrates to greater depths. The need for this correction is suggested by a series of measurements on the angular distribution of light intensity at different depths.

Figures 2 to 7 are experimental measurements of the angular distribution of light intensities for different natural waters. In each section the origin is indicated by intersecting perpendicular lines, and the light intensities from various directions are indicated by the distance from the origin to the curve. Light measurements were taken in three planes. In the 0° section light intensities were measured in the vertical plane which passed through the sun and light receiver. The receiver itself was a photo-cell in a water-tight case which was rotated by 10° steps. A cylinder with diaphragms was placed over the cell and the light received was limited to an angle of about 15°. The 90° section shows intensities in the vertical plane perpendicular to the 0° plane. Under conditions of a uniformly clouded sky there would be no difference between these sections. Readings were also taken when the receiver was pointed horizontally and rotated about a vertical axis.

In Fig. 2, which was taken in Trout Lake, Wisconsin, the relative increase in light intensity from vertically above as compared to the decrease from the direction of the solar beam is definite. The direction of the refracted solar rays is indicated by the elongated portion of each

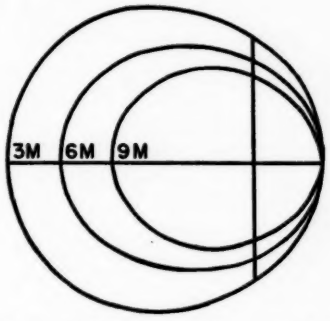

FIG. 3. Light vector diagram of readings taken in horizontal plane. Trout Lake, Wisconsin, August, 1937

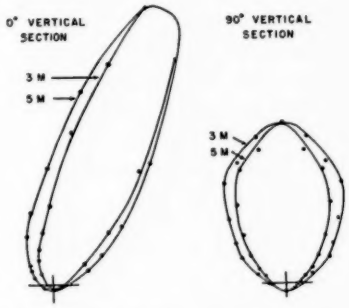

FIG. 4. Vertical section light vectors taken at Woods Hole Harbor, August 23, 1939.

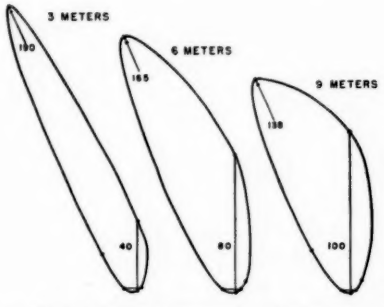

FIG. 2. Light vector diagram in 0° vertical plane including sun. Readings taken at Trout Lake Wisconsin, August, 1937.

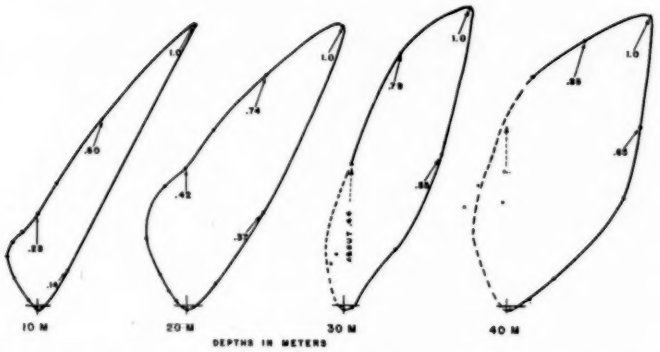

FIG. 5. 0° vertical section light vectors taken just beyond Continental Shelf at 39° 34′ N latitude and 71° 05′ W longitude, September 2, 1939.

curve where the relative intensities are 190, 165, and 138 at depths of 3, 6, and 9 meters, respectively. The intensity from below is made equal to one for all depths. In Fig. 3, where readings were taken in a horizontal plane, the readings directly away from the sun were all made arbitrarily equal to unity and it can be seen that as depth increases the pattern tends to become more symmetrical about a vertical axis. The 0° section of Fig. 4 and the sections of Fig. 5, in which the maximum readings are made to coincide, show the same tendency as Fig. 2; there is also the broadening with depth. Readings taken by the author were not sufficiently detailed to show the angular shift in the direction of maximum intensity toward the zenith with any great accuracy, but such shift was observed to take place. Pettersson has made quantitative measurements of such shift.[2]

The 90° vertical sections of both Figs. 4 and 6 are interesting in that they show a reverse effect: a sharpening of the pattern with depth. It seems reasonable to believe that there should be a common limit to both the broadening of one pattern and the sharpening of the other. Figure 7, which was taken under conditions of a uniformly clouded sky, also shows the sharpening of the pattern at greater depths and, more significantly, shows a definite trend toward a limiting pattern of light intensities. This limiting pattern has been defined by the author as that of *characteristic diffuse light*, and is discussed in connection with these results in an article on the angular distribution of characteristic diffuse light.[3] The pattern at great depths is symmetrical about a vertical axis, and is called characteristic inasmuch as it is characteristic of the optical properties of the water itself and independent of the angular distribution of light intensities incident at the surface.

If, in determining extinction coefficients, it is reasonable to apply a correction to light intensity readings taken in relatively shallow water to allow for the angle of the sun and the percent of sky energy, or, to allow for the angular distribution of light intensity near the surface, it is equally reasonable to apply the same type of correction to measurements taken in deeper water to allow for the characteristic angular

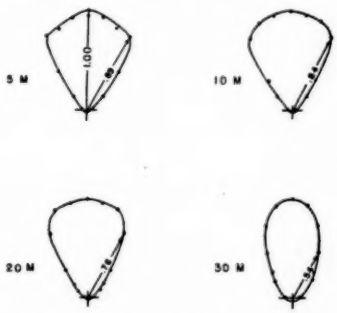

FIG. 6. 90° vertical section light vectors taken at same place and time as Fig. 5.

[2] Hans Pettersson, "Measurements of the angular distribution of submarine daylight," Rapports et Procès-Verbaux Conseil Perm. Internat. pour l'Exp. de la mer **108** (Pt. 2), 9 (1938).

[3] L. V. Whitney, "The angular distribution of characteristic diffuse light in natural waters," J. Marine Research, **4**, 122–131 (1941).

pattern approached at these depths. However, a somewhat disturbing question enters at this point which, in the author's opinion, seems fundamental. In the differential equation,

$$dI = -kIdx,$$

which is the basis of the exponential law, if there is any effect on the reduction of light intensity, dI, which is related to the angular distribution of light intensity at a given point it must be presumed that such effect is similar at every other point. In other words, the fundamental differential equation must presume that the angular distribution of light does not change with depth or distance traveled, or, that a steady-state condition has been reached. The question is, *what steady-state condition?*

In some natural waters having high extinction coefficients there is evidence that the characteristic pattern is fairly well established at about 3 meters in depth; in other waters it is not well established until after 20 meters or more, hence, it is unlikely that this pattern is met with in laboratory measurements of the extinction coefficient. It is probably safe to say that in laboratory measurements the light intensity is almost wholly unidirectional and that light intensities from other directions as measured at any point in the tube could be neglected. If a long tube were used, however, a gradual change of light distribution pattern might develop along the length of the tube depending on the character of the side walls. This change should alter the measured value of the extinction coefficient. In the mathematical analysis of the problem which follows *it is assumed that the extinction coefficient of the ordinary exponential law is based on measurements where the beam is essentially unidirectional at each point in its path.* It is further assumed that when scattering takes place from large particles, half the scattered light is generally forward and half backward. There may be some difficulty in reconciling these assumptions with each other, but they appear the simplest to handle.

Mathematical Analysis of Problem

In the derivation of a general law of diminution of light intensity it is first assumed that as light penetrates to great depths a limiting pattern is approached which has a maximum intensity from above. This assumption is based on experimental evidence already cited. In addition to this evidence the author has also found that the ratio of light intensity directed downward to that directed upward remains approximately constant with depth in optically homogeneous water. On the basis of such measurements scattering coefficients have been determined.[4] The assumption also appears reasonable when the factors which

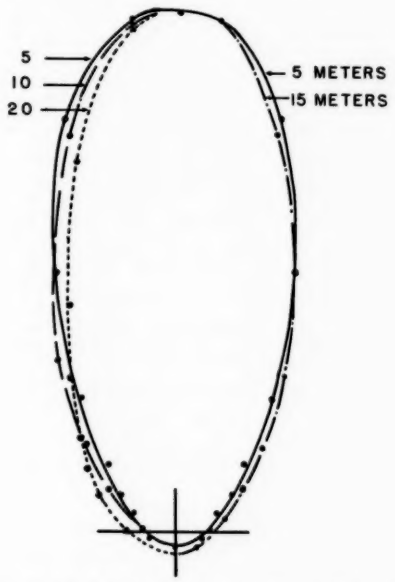

FIG. 7. Vertical section light vectors under conditions of evenly clouded sky and taken ¾ SSE of Tarpaulin Cove Light in Vineyard Sound, August 26, 1939.

affect the directional properties of light are considered. As light penetrates more deeply the relative intensity of the vertical rays tends to increase because of the more rapid absorption of the slanting rays. On the other hand, the scattering of light by suspended particles has an opposite effect, and tends to make light more equally distributed in direction. Eventually these influences should balance each other. The distribution pattern which results has already been defined as that of characteristic diffuse light. This pattern, once set up, should continue to be

[4] L. V. Whitney, "Transmission of solar energy and the scattering produced by suspensoids in lake waters," Trans. Wis. Acad. Sci. Art. and Let. **31**, 201–218 (1938).

maintained at greater depths by the balance between absorption and scattering, and the shape of it should depend on the relative values of the scattering and absorption coefficients. If scattering is small compared to absorption it seems reasonable the pattern should be long and narrow; if scattering is relatively large the pattern should be wider. The following derivation does not require that the shape of the limiting pattern be known, and no attempt is made here to calculate it.

The second assumption, which is probably only approximately true, is that when light is scattered from small particles it is scattered equally in all directions. This assumption is often made in the treatment of scattered light.[6] It is also easy to show that if scattering particles behave similarly to perfectly reflecting spheres, the intensity of scattered light per unit solid angle sent out *from* any small scattering particle is the same in all directions.

In the derivation of the general law the light at any depth is considered for mathematical purposes as consisting of two parts: that direct part which as yet has not been subject to any scattering, and the remainder which will be called diffuse light. The diffuse light so defined is continuously being recruited from the direct light. In the following treatment the phrase *direct light* or *direct radiation* will always refer to the radiation from sun and sky as yet unaffected in direction by scattering.

When applied to natural waters the simple differential equation

$$dI_x = -kI_x dx \tag{1}$$

from which the exponential law

$$I_x = I_0 e^{-kx} \tag{2}$$

is derived refers to the total light directed downward and includes both the direct and diffuse light. In these equations dI_x is the change of light intensity through a layer of thickness dx, I_x is the radiant energy per sq. cm at a depth x as measured by a *horizontal* flat receiver, k the extinction coefficient, x the depth, I_0 the radiant intensity at zero depth, and e the base of natural logarithms. In all discussions light of a single wave-length, or of a single extinction coefficient, is assumed. In calculating the total light directed downward k may be written as $a+s/2$, where a is the absorption coefficient and s the scattering coefficient. (Some writers take $2s$ as the scattering coefficient and k equal to $a+s$.) This is in accord with the second assumption that light is scattered equally in all directions, or, half the light is scattered upward and half downward. The treatment which follows would be unchanged if experimental evidence indicated that some fraction other than $s/2$ should be used as part of k. The total light directed downward will mean the total light energy passing downward through a horizontal unit area regardless of angle. This is the energy ordinarily measured by a flat receiver in a horizontal plane barring reflection losses at the glass surface.

If the distance, x, in Eqs. (1) and (2) means depth, then these equations as they stand are valid only when the light comes from directly overhead. When light comes from a different angle the distances must be multiplied by a correcting factor to allow for the average additional distance traveled by the light. If there were but a single beam at an angle r with the zenith, the correcting factor would be $1/\cos r$, and in this case the reflecting factor would be equal numerically to the distance traveled by the light in reaching a depth of one meter. When both sun and sky contribute to the incident radiation the correcting factor is taken as the mean path length already defined. It may be objected at this point that the mean path length of direct light should change with depth due to the more rapid absorption of the slanting rays. There is a variation but it is small and it becomes appreciable in amount only in the deeper water. But here it may be ignored because of the increasing predominance of the characteristic diffuse light. There is also some variation of mean path length with extinction coefficient but calculations show that this is negligible. If b be defined as the mean path length Eqs. (1) and (2)

[5] Sir Arthur Schuster and John William Nicholson, *Introduction to the Theory of Optics* (Longmans, Green & Company, 1924), third edition, p. 271.

[6] Nils G. Johnson and Gosta Liljequist, "On the angular distribution of submarine daylight and on the total submarine illumination," Svenska Hydrografisk-Biologiska Kommissionens Skrifter Ny serie: Hydrografi **14**, 3–15 (1938).

become:

$$dI_x = -(a+s/2)I_x b dx, \tag{3}$$

$$I_x = I_0 e^{-(a+s/2)bx} = I_0 e^{-kbx}. \tag{4}$$

These equations must now be modified to allow for the difference in penetrating properties of diffuse light directed downward and the direct sun and sky radiation. The direct radiation has a penetrating power indicated by its mean path length b already defined. It is assumed that the diffuse light, which increases in proportion with depth, has a penetrating power indicated by its mean path length, p. In each case the mean path length is related to the particular angular distribution of energy, and is that distance which a single unidirectional beam of light could travel and be diminished by the same percent as is the actual light traveling one meter deeper. According to Fig. 1 the mean path length of direct sun and sky light under ordinary experimental conditions varies from 105 to 135 centimeters per meter depending on the angle of the sun and percent sky radiation. The mean path length of characteristic diffuse light, on the other hand, should depend on the optical properties of the water itself, or, more particularly, on the relative values of the scattering and absorption coefficients. Calculations based on some deep water patterns of light intensity show values for p in the neighborhood of 130 centimeters per meter.

The diminution of total light intensity directed downward in a layer of thickness dx is the sum of two parts: the reduction of the direct light, dL_x, plus the reduction of the diffuse light, dM_x. This fact may be stated by the differential equation

$$dI_x = dL_x + dM_x \tag{5}$$

or

$$dI_x = -kL_x b dx - kM_x p dx, \tag{6}$$

where dI_x is the total reduction of light intensity, k is the ordinary extinction coefficient, b the mean path length of direct light, p the mean path length of diffuse light, L_x the direct light intensity, and M_x the diffuse light intensity. The direct light intensity, L_x, which is required for substitution into Eq. (6), is obtained by solving the differential equation

$$dL_x = -jL_x b dx \tag{7}$$

where j is the extinction coefficient for the direct light.* Since the direct light has been defined as that exclusive of any scattered back in the downward direction, the extinction coefficient j equals $a+s$ or $k+s/2$. The direct light intensity is that which would be present if light which is scattered were absorbed instead. The solution of Eq. (7) is

$$L_x = L_0 e^{-jbx} = I_0 e^{-jbx}. \tag{8}$$

At the surface the total intensity is the direct intensity and hence $L_0 = I_0$.

The diffuse light intensity, M_x, is the total intensity minus the direct intensity:

$$M_x = I_x - L_x = I_x - I_0 e^{-jbx}. \tag{9}$$

Substituting L_x from Eq. (8) and M_x from Eq. (9) into Eq. (6):

$$\frac{dI_x}{dx} + kpI_x = kI_0(p-b)e^{-jbx}. \tag{10}$$

This is a linear differential equation of the first order the solution of which is

$$I_x = I_0 \frac{k(p-b)}{kp-jb} e^{-jbx} + Ce^{-kpx}. \tag{11}$$

If v be defined as $sb/2k(p-b)$, the solution may be written more simply as

$$I_x = I_0 e^{-jbx}/(1-v) + Ce^{-kpx}. \tag{12}$$

The constant C may be obtained by imposing the boundary condition that I_x equals I_0 when x equals zero:

$$I_0 = I_0 1/(1-v) + C. \tag{13}$$

Solving for C,

$$C = -I_0 v/(1-v). \tag{14}$$

* It is to be noted that the dL_x of Eq. (5) differs from the dL_x of Eq. (7). In the derivation of the exponential law of decrease of direct light intensity the extinction coefficient j must be used for reasons stated immediately following Eq. (7); however, the extinction coefficient k must be used in calculating any diminution of total light intensity because light scattered downward even from the direct beam continues to contribute to the total light intensity.

Substituting into Eq. (12):

$$I_z = I_0\left(\frac{e^{-jbz}}{1-v} - \frac{ve^{-kpz}}{1-v}\right).^* \qquad (15)$$

This general law of diminution of light intensity takes into account the fact that the percent of diffuse light increases with depth; it also allows for the difference in mean path length of the diffuse light compared with the mean path length of the direct sun and sky radiation.

The ordinary exponential law follows from the general law under special conditions. If scattering be negligible, or if conditions be such that the mean path length of diffuse light is the same as for direct light the general law reduces to the simple exponential form, Eq. (2).

The percent of diffuse light directed downward at any depth may be calculated on the basis of the general law. This fraction is

$$F_z = M_z/I_z = (I_z - L_z)/I_z. \qquad (16)$$

If the value of the direct light, L_z, from Eq. (8), and the value of the total light intensity directed downward, I_z, from Eq. (15) be substituted in this expression we have

$$F_z = \frac{1-e^{-mz}}{1-(e^{-mz}/v)}, \qquad (17)$$

where $m = jb - kp$. In cases where the general law reduces to the simple exponential form this equation reduces to

$$F_z = 1 - e^{-(s/2)bz}. \qquad (18)$$

Equations (15) and (17) require the measurement of several optical constants. The mean path length of sun and sky radiation, b, may be determined by methods outlined by the author and values read from Fig. 1. The total extinction coefficient, k, may be determined from experimental measurements of light intensities at different depths near the surface corrected for the mean path length of sun and sky radiation. The scattering coefficient, s, is given by an equation derived by the author:

$$s = \frac{2b}{b - \log_e(1+b)}kR = F(b)kR. \qquad (19)$$

R is the ratio of the total light intensity directed upward to that directed downward. It was found that this ratio remains approximately constant with depth in optically homogeneous water. The above expression was obtained by integrating over-all scattering centers below the receiver to obtain the total light intensity directed upward.[4] The expression is an approximation insofar as it was assumed that the total light intensity directed downward at any depth followed the simple exponential law rather than the general law, Eq. (15). However, the approximation is sufficiently close for two reasons: First, the departure from the simple exponential law is small excepting in extreme cases (Table I); second, the most important contribution to the scattered light directed upward originates immediately below the receiver where the downward intensity is greatest, and hence variations from the simple exponential law, which are appreciable only over large depths, may be neglected. No method has as yet been devised

* The author's attention has been called to the fact that Eq. (15) above does not resemble an equation given in Schuster and Nicholson, *Introduction to the Theory of Optics* (1924), third edition, p. 271, which applies to light in which scattering preponderates. There is no reason why these equations should have any resemblance. Equation (15) is based on the idea, supported by experimental evidence in natural waters, that as depth increases a steady-state condition is gradually established as diffuse light becomes more and more predominant. This condition is, in a sense, the result of a balance between scattering and absorption in their effects on the angular distribution pattern of light intensities. In Schuster and Nicholson's treatment of the problem several conditions stated are not in accord with the experimental facts upon which Eq. (15) is based. First, they assume a situation where "we may imagine a thick layer of the medium in which a general radiation equal in all directions falls on one surface. . . ." Their final equation on the page which applies to a very thick layer,

$$A = B = E(1 - x/t)$$

reduces to this situation exactly at the initial surface or where x, the depth, equals zero. (A is the intensity directed downward, at any depth, B that directed upward at a given depth, and E the radiation which enters the initial surface.) But the radiation from sun and sky is definitely not equal in all directions as it falls on a water surface, and that scattered back upward from a water surface is not at all equal to that incident upon it. Second, the argument presumes scattering but no absorption. In natural waters there is always absorption and it usually predominates; in fact, the steady-state condition eventually reached, as shown by experimental evidence, requires absorption to balance scattering. Finally, a consequence of the initial conditions stated by Schuster and Nicholson is that $A - B$ is constant. This is not in accord with experimental conditions in natural waters. Rather, the ratio of light directed downward to that directed upward, or, A/B is a constant in optically homogeneous deep water. This latter fact is again consistent with the steady-state conditions in deep water.

TABLE I. *Comparison between the general diminution law and the simple exponential law. Calculations are based on experimental measurements of extinction coefficients k, and on ratios of upward to downward light intensities R. Scattering coefficients are calculated by Eq. (19). Average calculated values of mean path length of direct light and assumed values of mean path length of characteristic diffuse light are used for both lakes. The table is based on the following values of optical constants:*

	Trout Lake	*Little John Lake*
k	0.375	0.994
s	.045	.258
R	.020	.048
b	1.18	1.18
p	1.28	1.28

*These values are based on earlier work by the author.**

	Total Light Intensity Directed Downward				Percent Characteristic Diffuse Light Directed Downward			
	Trout		Little John		Trout		Little John	
Depth in Meters	Gen. L. Eq. (15)	Exp. L. Eq. (2)	Gen. L. Eq. (15)	Exp. L. Eq. (2)	Gen. L. Eq. (17)	Exp. L. Eq. (18)	Gen. L. Eq. (17)	Exp. L. Eq. (18)
0	100.0	100.0	100.0	100.0	0.0	0.0	0.0	0.0
2	40.0	41.4	9.55	9.65	5.1	5.0	24.8	26.5
4	16.4	17.0	0.85	0.93	9.8	10.0	40.6	45.6
6	6.53	7.00	0.075	0.0897	13.9	14.9	51.4	60.0
10	1.11	1.19			20.9	23.1		

* See reference 4 in text.

by the author for determining the mean path length of characteristic diffuse light, p. An experimental value of p might be determined from readings taken at great depths where the direct light content is negligible, provided the total extinction coefficient, k, were reliably known. If water be optically homogeneous the value of k determined from measurements near the surface, where direct light predominates, could be used for measurements at greater depths. In Table I, values which seem reasonable have been arbitrarily assumed for p. In many cases the mean path length of diffuse light cannot be greatly different from the mean path length of direct light since semi-logarithmic graphs of light intensity against depth are approximately straight lines beyond the first meter.

Comparison between the General Diminution Law and the Simple Exponential Law

In Table I, light intensities at various depths as calculated by the simpler and more exact laws are compared. Trout Lake and Little John Lake were chosen for this comparison because of the difference in optical properties of the lakes. Trout Lake is relatively transparent, and Little John Lake has a large amount of scattering. In the case of Trout Lake there is little difference in either the total light intensity directed downward or in the percent of characteristic diffuse light as calculated according to the two laws. This result is to be expected since scattering is small. In Little John Lake differences in calculated values are small near the surface. Again, this is to be expected since the proportion of direct light in shallower water is much greater than in deeper water. The difference in the calculated values in the deeper water is naturally a reflection of the differences in the values of b and p, the mean path lengths of direct and diffuse light. As has already been mentioned, if p and b are the same, the general law reduces to the simpler exponential law. *Since the value of p has been arbitrarily assumed* for the purpose of illustrating the general law, differences shown merely illustrate the type of deviation which may be expected from the simpler law. The evidence on the change in angular distribution with depth indicates a longer path length, in some cases, for diffuse light than for direct light. However, the reverse may be true in other cases. The mean path length for diffuse light was assumed 10 centimeters longer than for direct light. The fact that a method of calculating mean path lengths for characteristic diffuse light has not as yet been derived does not invalidate the general diminution law, but merely means that one of the constants appearing in it is yet

to be determined. The author hopes to devise a method of calculating this constant in terms of the scattering and extinction coefficients. Such calculations could then be compared with experimental measurements of mean path lengths in optically homogeneous water.

SUMMARY

1. A study of the angular distribution of light intensity at difference depths shows an increase of scattered light in deeper water, and the tendency for the angular distribution pattern to become symmetrical about a vertical axis with the maximum intensity from the zenith. Two opposing factors tend to produce a limiting angular distribution pattern for diffuse light at great depths: the more rapid absorption of slanting rays which tends to make the light more directional, and the scattering by particles which tends to make the light less directional.

2. A general law of diminution of light intensity, was derived which allowed for both the changing percent of diffuse light with depth, and the mean path length of characteristic diffuse light which may differ from the mean path length of direct sun and sky radiation. In the solution of the problem, the light at any given depth was considered as being made up of two parts: the direct sun and sky radiation with a mean path length depending on the angle of the sun and the percent of sky energy, and the diffuse light with its characteristic path length. The problem is somewhat analogous to the calculation of the penetration of light made up of two wave-lengths with different extinction coefficients; in this case each wave-length may be considered separately. The analogy breaks down at this point, however, for, while the direct and diffuse light may be considered distinct at any one depth, they cannot be considered separate from each other in calculating intensities at still greater depths since the direct light is gradually converted into diffuse light. The general law is derived by solving two simultaneous differential equations.

3. The total light intensity directed downward and the percent of characteristic diffuse light directed downward was calculated for different depths for two Wisconsin lakes on the bases of both the general diminution law and the simpler exponential law.

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Wall Materials and Lighting

PARRY MOON
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received September 2, 1941)

I. INTRODUCTION

THE use of white or near-white for the ceilings of rooms has now become almost universal, largely as the result of a recognition of the importance of the ceiling in the lighting of a room. The effect of high reflection factors for the walls is not generally recognized; though the effect of the walls may be fully as great as that of the ceiling, particularly for rooms with relatively high ceilings. Not only do highly reflecting walls allow a more economical lighting installation for the same illumination on the work, but—what is perhaps more important—they reduce contrasts and tend toward a more pleasing psychological effect.

The present paper continues the previous work[1] by listing the reflection factors and trichromatic coefficients of 87 commercially available wall materials such as washable fabrics, wood veneers, and wall boards. The methods of test and computation were the same as described previously.[1] The Hardy photoelectric spectrophotometer was used,[2] and computations were made for both illuminants *A* and *C*, corresponding, respectively, to incandescent light and to daylight.[3] The data are then used in a consideration of the lighting of a cubical room.

2. RESULTS

Figures 1 to 6 show representative spectrophotometric curves, the designating numbers on the right margins referring to column 1 of Table I. Curves for other samples of wall boards and wood veneers can be found in a previous publication.[4] Table I gives the true reflection factor ρ and the trichromatic coefficients x and y for all the wall materials that were tested. The column marked "Mfgr." refers to Table II of the paper on acoustical materials.[1] Under "Approx. Color" an attempt has been made to give a rough idea of the appearance of the material. Most of the wood veneers had apparently been coated with a transparent varnish. This finish is called "natural" in Table I, though the treatment undoubtedly produces a slightly lower reflection factor and a somewhat yellower color than would be obtained with a freshly cut wood surface. A few samples were stained (No. 199, for instance) and were much darker than the natural wood.

Micarta samples were obtained with both polished and matt surfaces but only the matt surfaces were tested. The Marlite wall boards

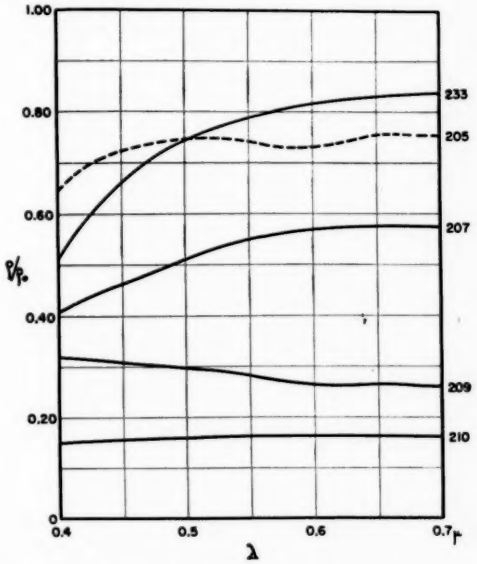

FIG. 1. Spectrophotometric curves for white and gray wall materials.

[1] Parry Moon, "Optical reflection factors of acoustical materials," J. Opt. Soc. Am. **31**, 317 (1941); "Colors of ceramic tiles," J. Opt. Soc. Am. **31**, 482 (1941).

[2] A. C. Hardy, "History of the design of the recording spectrophotometer," J. Opt. Soc. Am. **28**, 360 (1938).

[3] It is a pleasure to acknowledge the assistance of the staff of the Color Measurements Laboratory at Massachusetts Institute of Technology and the help of Messrs. E. D. Benson, F. Carroll, L. E. Duval, J. M. Fiore, J. Margolskee, J. P. Reilly, D. L. Shapiro, N. A. Teixeira, and W. R. Thurston, who did most of the computation, with the support of the National Youth Administration. Thanks are also tendered to the manufacturers who supplied samples of wall materials.

[4] Parry Moon, "Color determination," Illum. Eng. **36**, 313 (1941).

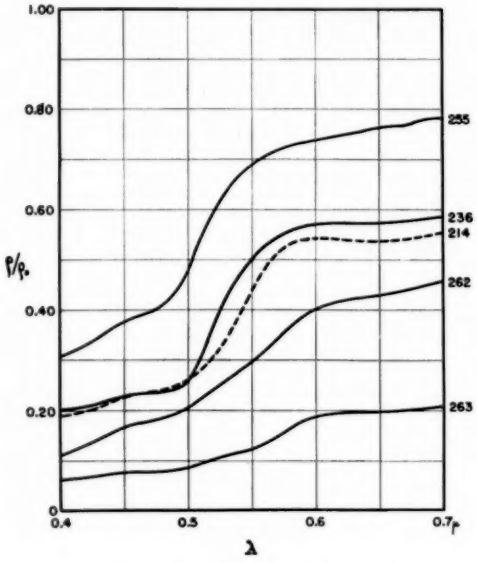

FIG. 2. Cream, buff, and brown materials.

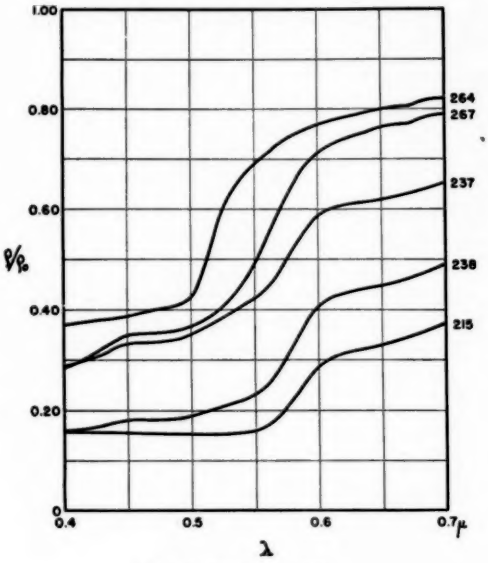

FIG. 4. Pink materials.

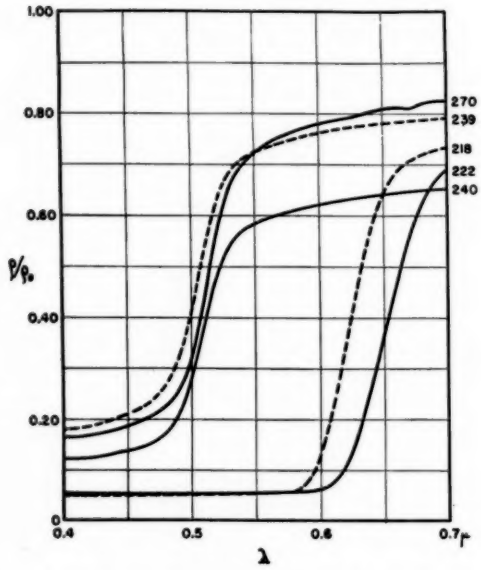

FIG. 3. Red and yellow materials.

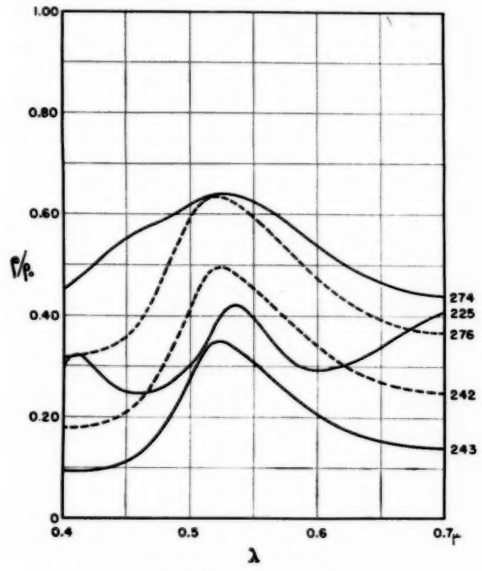

FIG. 5. Green materials.

had a hard surface layer of colored material cemented to a heavy backing. Flexboard and Transite are asbestos products with hard, smooth surfaces. The asphalt tiles were specially designed for use on walls. Wall-Tex is a washable fabric, while the other materials listed in the last section of Table I are wall linoleums.

3. APPLICATION TO ROOM LIGHTING

It is interesting to consider the practical application of these data to the problem of room

lighting. The following analysis will be confined to a cubical room, indirectly lighted by incandescent lamps, though the method is equally applicable to any other condition. The ceiling will be non-selective white having a reflection factor of $\rho_2=0.80$, while the floor will be black. The table height will be equal to one-quarter the distance between ceiling and floor. What effect on lighting conditions is obtained by changing the material used for the walls?

A few materials of Table I are listed again in Table II. These particular samples were chosen at random, and whatever is said about them must not be construed as indicating that they are better or worse than other materials of Table I. The luminous flux densities at various parts of the room and with any of the wall materials can be calculated by the methods of a previous paper.[5] The fourth column of Table II gives the ceiling luminosity L_2 (lumens per unit area) in terms of ceiling luminosity L_{02} that would be produced if there were no interreflections of light within the room. With dark materials, such as wood paneling Nos. 202 and 203, very little light is reflected back to the ceiling and L_2/L_{02} is only slightly above unity. As the wall reflection factor is raised, however, the resulting ceiling luminosity is seen to increase.

The fifth and sixth columns give calculated values of wall luminosity L_1 when the walls of the room are completely covered with the various materials. In indirectly lighted rooms, the walls are brightest at the ceiling and become progressively less bright as the floor is approached. Curves of L_1 *vs.* distance are easily calculated[5] but will not be given here. Instead, column 5 lists the luminosity ratio near the ceiling, while column 6 is for desk level.

The average illumination E_{hv} on a horizontal plane at desk level is given in the seventh column. Note the rather surprising result that with identical ceiling and floor, and *with identical lighting equipment, over three times as much useful light is received in the first case as in the last.* On the basis of economy, therefore, high reflection factors are recommended for the walls of rooms.

[5] Parry Moon, "Interreflections in rooms," J. Opt. Soc. Am. **31**, 374 (1941).

This conclusion is also evident from the last column of Table II, where the illumination for $\rho_1=0.78$ is taken as 100 percent and the values for other materials are referred to this norm. Even the use of a medium green for the walls will require approximately twice as large a lighting system, twice the heat, and almost twice the electric bill for the same illumination as would be obtained with white walls. A change from prima vera to walnut paneling will require 50 percent increase in the lighting system to provide the same illumination. In agreement with these theoretical results, the lighting technician has found by experience that small offices paneled in dark wood cannot be lighted satisfactorily. The same may be said of library reading rooms that have been designed by architects of the old school. In such cases, economy forces the lighting expert to abandon the indirect system and to embrace some form of direct lighting with its glare and harsh shadows.

Table III continues the analysis from the standpoint of visual comfort. Numerous researches show that best visual conditions are obtained when the whole field of view has approximately the same luminosity. Measurements of the luminosity distributions found in na-

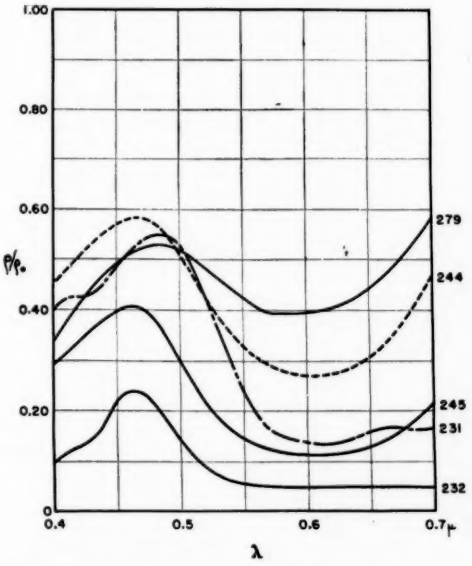

FIG. 6. Blue materials.

TABLE I. *Reflection factors and trichromatic coefficients.*

No.	Name	Mfgr.	Approx. Color	A			C		
				x	y	ρ	x	y	ρ
			Wood Veneers						
193	Marlite, prima vera	19	Natural	0.5112	0.4217	0.447	0.3891	0.3818	0.417
194	Marlite, avodire	19	Natural	0.4997	0.4184	0.401	0.3804	0.3764	0.378
195	Marlite, white oak	19	Natural	0.5192	0.4081	0.281	0.3985	0.3739	0.259
196	Texboard, avodire	6	Brown	0.5168	0.4148	0.276	0.4010	0.3834	0.256
197	Marlite, zebrawood	19	Natural	0.5239	0.4074	0.214	0.4047	0.3765	0.196
198	Marlite, lacewood	19	Natural	0.5383	0.4013	0.158	0.4263	0.3706	0.140
199	Texboard, mahogany	6	Dk. red	0.5533	0.3932	0.144	0.4400	0.3704	0.127
200	Marlite, walnut (plain)	19	Natural	0.5192	0.4070	0.140	0.3965	0.3639	0.127
201	Texboard, walnut	6	Dk. brown	0.5239	0.4027	0.110	0.3990	0.3634	0.102
202	Marlite, claro walnut	19	Natural	0.5122	0.4056	0.106	0.3866	0.3596	0.0976
203	Marlite, oriental wood	19	Natural	0.5056	0.4049	0.0955	0.3760	0.3503	0.0886
			Wall Boards						
204	Marlite, white	19	White	0.4506	0.4096	0.893	0.3140	0.3219	0.890
205	Micarta 856	32	White	0.4482	0.4088	0.723	0.3111	0.3199	0.724
206	Marlite, ivory	19	Ivory	0.4970	0.4278	0.649	0.3844	0.3859	0.566
207	Flexboard, light gray	15	Lt. gray	0.4607	0.4139	0.540	0.3268	0.3355	0.534
208	Cemesto	6	Gray	0.4591	0.4139	0.502	0.3250	0.3343	0.497
209	Micarta 893	32	Lt. gray	0.4352	0.4052	0.272	0.2970	0.3061	0.276
210	Flexboard, dark gray	15	Dk. gray	0.4469	0.4140	0.164	0.3134	0.3216	0.161
211	Micarta 404	32	Black	0.4464	0.4064	0.0529	0.3085	0.3137	0.0532
212	Ins. bd., tempered, black	15	Black	0.4475	0.4103	0.0492	0.3093	0.3218	0.0493
213	Micarta 890	32	Cream	0.4919	0.4242	0.649	0.3729	0.3760	0.616
214	Flexboard, buff	15	Buff	0.5039	0.4207	0.457	0.3884	0.3773	0.426
215	Flexboard, rose	15	Red	0.5134	0.3883	0.215	0.3747	0.3252	0.196
216	Panel board	6	Brown	0.5208	0.4078	0.208	0.4008	0.3714	0.191
217	Hard board	6	Brown	0.5188	0.4074	0.205	0.3980	0.3681	0.188
218	Micarta 894	32	Red	0.6196	0.3356	0.134	0.5051	0.3113	0.102
219	Tempered hard board	6	Brown	0.5183	0.4056	0.120	0.3937	0.3620	0.110
220	Micarta 830	32	Brown	0.5394	0.3902	0.0969	0.4146	0.3508	0.0859
221	Masonite tempered presdwood	20	Dk. red	0.5071	0.4119	0.0960	0.3879	0.3582	0.0865
222	Micarta 895	32	Dk. red	0.5640	0.3547	0.0852	0.4129	0.3105	0.0728
223	Micarta 805	32	Dk. brown	0.4758	0.4068	0.0692	0.3392	0.3323	0.0669
224	Micarta 801	32	Dk. red	0.4797	0.3988	0.0632	0.3385	0.3223	0.0608
225	Flexboard, green	15	Green	0.4354	0.4456	0.350	0.3175	0.3579	0.338
226	Marlite, pheasant green	19	Green	0.4261	0.4567	0.321	0.3116	0.3922	0.332
227	Micarta 896	32	Lt. green	0.3813	0.4386	0.311	0.2560	0.3471	0.342
228	Transite, green	15	Green	0.4524	0.4292	0.302	0.3245	0.3554	0.303
229	Ins. bd., tempered, green	15	Dk. green	0.4429	0.4299	0.0696	0.3153	0.3528	0.0706
230	Marlite, robin-egg	19	Blue	0.3958	0.4346	0.330	0.2736	0.3364	0.353
231	Micarta 887	32	Blue	0.3225	0.3796	0.219	0.2104	0.2479	0.258
232	Micarta 898	32	Dk. blue	0.3224	0.3221	0.0614	0.2072	0.1917	0.0717
			Asphalt Tiles						
233	Tile-Tex 170	29	White	0.4605	0.4144	0.780	0.3267	0.3369	0.773
234	Tile-Tex 171	29	Black	0.4451	0.4063	0.0452	0.3069	0.3138	0.0462
235	Tile-Tex 187	29	Cream	0.4824	0.4229	0.671	0.3584	0.3647	0.647
236	Tile-Tex 188	29	Cream	0.5015	0.4273	0.497	0.3913	0.3854	0.461
237	Tile-Tex 189	29	Pink	0.4972	0.4056	0.481	0.3654	0.3448	0.453
238	Tile-Tex 190	29	Pink	0.5213	0.3962	0.301	0.3922	0.3464	0.274
239	Tile-Tex 185	29	Yellow	0.5002	0.4432	0.697	0.3984	0.4270	0.664
240	Tile-Tex 186	29	Yellow	0.5076	0.4452	0.561	0.4129	0.4392	0.529
241	Tile-Tex 191	29	Red	0.5951	0.3557	0.191	0.4814	0.3269	0.151
242	Tile-Tex 183	29	Lt. green	0.4347	0.4584	0.387	0.3203	0.4010	0.400
243	Tile-Tex 184	29	Lt. green	0.4270	0.4737	0.251	0.3189	0.4257	0.263
244	Tile-Tex 181	29	Lt. blue	0.3907	0.3802	0.317	0.2516	0.2601	0.342
245	Tile-Tex 182	29	Blue	0.3467	0.3462	0.145	0.2198	0.2139	0.165

TABLE I.—*Continued.*

WALL LINOLEUMS AND SIMILAR MATERIALS

No.	NAME	MFGR.	APPROX. COLOR	A			C		
				x	y	ρ	x	y	ρ
246	Wall-Tex 3097	9	Ivory	0.4653	0.4135	0.770	0.3314	0.3389	0.756
247	Wall-Tex 3000	9	White	0.4577	0.4131	0.761	0.3228	0.3333	0.754
248	Wall-Tex 3098	9	White	0.4586	0.4131	0.759	0.3238	0.3339	0.751
249	Wall-Tex 3090	9	Ivory	0.4670	0.4134	0.754	0.3331	0.3400	0.739
250	Wall-Tex 3001	9	Ivory	0.4719	0.4184	0.727	0.3434	0.3486	0.701
251	Linowall, 737	1	Ivory	0.4768	0.4202	0.679	0.3483	0.3609	0.660
252	Wall-Tex 3006	9	Ivory	0.4727	0.4160	0.675	0.3418	0.3477	0.656
253	Wall-Tex 3036	9	Ivory	0.4732	0.4200	0.583	0.3447	0.3541	0.567
254	No. 7972	10	Lt. gray	0.4652	0.4166	0.417	0.3326	0.3464	0.412
255	Wall-Tex 3003	9	Cream	0.4865	0.4264	0.680	0.3648	0.3793	0.656
256	Linowall, 734	1	Cream	0.4840	0.4301	0.675	0.3642	0.3858	0.652
257	Wall-Tex 3010	9	Cream	0.4933	0.4266	0.665	0.3744	0.3841	0.633
258	Wall-Tex 3093	9	Cream	0.4898	0.4214	0.643	0.3664	0.3704	0.614
259	Wall-Tex 3017	9	Cream	0.5050	0.4263	0.575	0.3908	0.3882	0.538
260	No. 7973	10	Buff	0.4866	0.4200	0.560	0.3622	0.3671	0.538
261	No. 7977	10	Buff	0.4745	0.4197	0.502	0.3463	0.3576	0.490
262	No. 7981	10	Lt. brown	0.5093	0.4151	0.329	0.3906	0.3741	0.307
263	No. 7982	10	Brown	0.5153	0.4091	0.147	0.3948	0.3642	0.135
264	Wall-Tex 3012	9	Pink	0.4915	0.4227	0.689	0.3700	0.3719	0.656
265	Wall-Tex 3033	9	Pink	0.4944	0.4168	0.676	0.3703	0.3620	0.637
266	No. 7992	10	Pink	0.4769	0.4158	0.586	0.3470	0.3514	0.569
267	Wall-Tex 3011	9	Pink	0.5076	0.4059	0.576	0.3814	0.3525	0.532
268	No. 7975	10	Pink	0.4884	0.4111	0.552	0.3580	0.3512	0.529
269	No. 7989	10	Pink	0.5028	0.4068	0.506	0.3742	0.3535	0.473
270	Wall-Tex 3019	9	Yellow	0.5089	0.4409	0.698	0.4118	0.4303	0.654
271	Wall-Tex 3099	9	Yellow	0.4941	0.4216	0.655	0.3730	0.3785	0.624
272	No. 7987	10	Yellow	0.4971	0.4238	0.571	0.3789	0.3828	0.543
273	No. 7963	10	Yellow	0.4961	0.4288	0.560	0.3807	0.3914	0.535
274	Wall-Tex 3032	9	Lt. green	0.4320	0.4216	0.568	0.3014	0.3315	0.581
275	Wall-Tex 3034	9	Lt. green	0.4447	0.4350	0.560	0.3207	0.3610	0.566
276	Wall-Tex 3023	9	Lt. green	0.4339	0.4430	0.523	0.3118	0.3728	0.538
277	No. 7988	10	Lt. green	0.4462	0.4172	0.435	0.3123	0.3367	0.441
278	No. 7971	10	Lt. green	0.4484	0.4317	0.398	0.3238	0.3613	0.403
279	Linowall, 731	1	Lt. blue	0.4313	0.4022	0.415	0.2912	0.3053	0.426

tural scenery[6] show that rarely does the ratio L_{max}/L_{min} exceed 10. One may conclude that in an ideal lighting system,

$$L_{max}/L_A < 3,$$
$$L_A/L_{min} < 3,$$

where

L_{max} = maximum luminosity in the field of view,
L_{min} = minimum luminosity in the field of view,
L_A = luminosity to which fovea is adapted.

In Table III, the adapting luminosity is taken as the luminosity of white paper ($\rho = 0.80$) on a desk. This assumption would correspond to the common visual task of reading or doing clerical work. The ratios L/L_A and L_A/L for walls and ceiling are obtained from the data of Table II. Column 5 of Table III shows that as the reflection factor of the walls is reduced, the luminosity of the ceiling must be increased (for L_A = const.). For the darker wall materials, the ceiling becomes uncomfortably bright, as has been found in practice.[7] It would seem that *the solution of the difficulty is to increase reflection factors, not, as many believe, to abandon indirect systems.*

Luminosity ratios for the walls are also unpleasantly large when dark materials are used, as shown by Table III. Indeed, one must conclude that an ideal lighting system cannot be obtained in a cubical room unless the reflection factor of the walls is over 0.50. This, as well as the numerical values of Tables II and III, are of course modified by the shape of the room. In large rooms with low ceilings, the walls play a minor part in the lighting; though even with a

[6] H. L. Logan, "Specification points of brightness," Trans. I.E.S. **34**, 881 (1939).

[7] Ward Harrison, "What is wrong with our 50 foot-candle installations?" Trans. I.E.S. **32**, 208 (1937).

TABLE II. *Effect of wall materials in a cubical room.*

No.	Description	ρ	Ceiling L_2/L_{02}	Walls $L_1(0)/L_{02}$	Walls $L_1(h)/L_{02}$	Illumination E_{av}/L_{02}	Illumination E/E_{233}
204	Wall board, white	0.893	1.47	0.91	0.41	0.79	1.27
233	Asphalt tiles, white	0.780	1.33	0.68	0.28	0.62	1.00
259	Washable fabric, cream	0.575	1.19	0.41	0.13	0.44	0.71
228	Asbestos board, green	0.302	1.08	0.17	0.045	0.31	0.50
210	Asbestos board, gray	0.164	1.04	0.090	0.020	0.26	0.42
193	Prima vera	0.447	1.13	0.29	0.085	0.37	0.60
202	Walnut	0.106	1.02	0.055	0.010	0.25	0.40
203	Oriental wood	0.0955	1.02	0.050	0.010	0.25	0.40

TABLE III. *Effect of wall materials in a cubical room.*

No.	Description	ρ	Work L_A/L_{02}	Ceiling L_2/L_A	$L_1(0)/L_A$	Walls $L_A/L_1(0)$	$L_A/L_1(h)$
204	Wall board, white	0.893	0.63	2.3	1.4		1.5
233	Asphalt tiles, white	0.780	0.50	2.7	1.4		1.8
259	Washable fabric, cream	0.575	0.36	3.3	1.2		2.8
228	Asbestos board, green	0.302	0.24	4.4		1.4	5.4
210	Asbestos board, gray	0.164	0.21	4.9		2.3	10.5
193	Prima vera	0.447	0.29	3.9	1.0	1.0	3.4
202	Walnut	0.106	0.20	5.2		3.6	20.0
203	Oriental wood	0.0955	0.20	5.2		3.9	20.0

L_A is the luminosity to which the fovea is adapted. L_A is assumed to be equal to the luminosity of white paper $\rho = 0.80$, placed horizontally at desk level.

room 60×30×3 meters, wall reflection factors are of some importance.

The equations for interreflections apply strictly only if the radiation is in a small enough wave-length band so that it can be considered as homogeneous.[8] The employment of the equations,[5] as in Tables II and III, is permissible only if the materials are approximately non-selective in the visible region. The degree of approximation entailed in this assumption is easily checked by going back to the spectrophotometric curves and considering separate homogeneous component ratiations at various wave-lengths. Each such radiation behaves independently of all the rest and its interreflections can be read directly off the graphs, Figs. 2 and 3, reference 5.

An example of this method of calculation is shown in Fig. 7. A highly selective yellow tile (No. 239) was taken, and values of ρ were read from Fig. 3 at intervals of 0.02μ. The corresponding values of radiant energy reaching the desk were then obtained from Fig. 2 of reference 5. For an equal-energy spectrum from the light source (curve 1, Fig. 7), the spectral energy distribution reaching the desk is shown by curve 2. The illumination of the desk is seen to

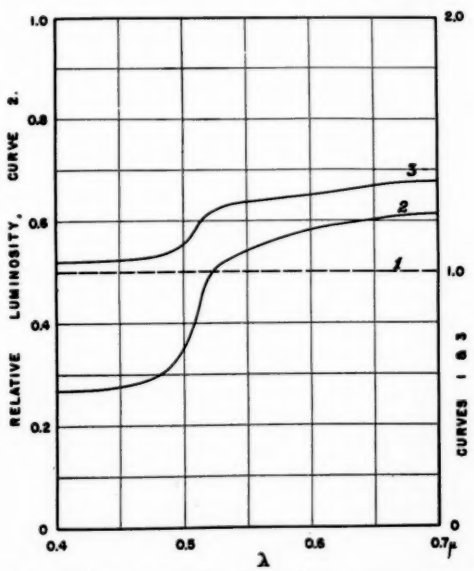

FIG. 7. Calculated spectral distribution curves for the radiant energy in a room with white ceiling and yellow walls (No. 239 tiles). (1) Equal energy spectrum from hypothetical light source; (2) Spectral distribution of the radiant energy reaching the desk level; (3) Spectral distribution of the radiant energy from the ceiling.

[8] Parry Moon, "On interreflections," J. Opt. Soc. Am. **30**, 195 (1940).

be less yellow than if all the light had been reflected from the tiles. Some of the light reaching the desk comes directly from the nonselective ceiling; but to it is added light from the walls, and each reflection from wall to wall makes the light a purer yellow. The composite result is curve 2.

The walls also give a slightly yellow appearance to the ceiling. Curve 3 shows the energy-distribution curve, obtained by use of Fig. 3 (reference 5). The ceiling is evidently a pale yellow, considerably less pure than the color of the light reflected from a piece of white paper on the desk. By multiplication of the curves of Fig. 7 by the spectral distribution curve for any desired kind of lamp, the resulting distribution curves and colors of ceiling and paper can be obtained.

Thus, on the basis of room lighting, white walls are found to be best. They allow the most economical lighting system, they reduce contrasts, and they do not modify the color of the light reaching the desk level. Popular objections are difficulty of cleaning and the fear that the room will look like a hospital. Modern wall materials (including modern gloss and semi-matt paints) eliminate the first objection. The second is met by using plenty of color in the furniture, floor, etc. The result is beautifully light and cheerful.

4. Conclusions

The paper presents data on light reflection from various wall materials. A new development in the integral-equation theory of interreflections makes possible, for the first time, the use of such data in the prediction of wall and ceiling luminosities in rooms.

To allow definite numerical results, a specific room is chosen. The room is cubical in shape, has a white ceiling, and is indirectly lighted. Calculations show that white walls are superior for the following reasons:

(1) *Economy.* The lighting system for the room with dark walls (walnut paneling, for instance) must supply 2 to 3 times the lumens that are required with white walls, desk illumination being the same in both cases.

(2) *Reduced contrasts.* With walls of low reflection factor, the ceiling is found to be unpleasantly bright while the walls are too dark. White walls reduce contrasts and thus improve seeing conditions.

(3) *Better color.* Calculations show that colored wall materials may seriously modify the spectral distribution of the radiant energy reaching the desk level. Ordinarily, colored light is not recommended for critical visual tasks; and if it is needed for special purposes, it can be obtained most economically by the use of special lamps and white walls.

Symposium on Spectrographic Analysis

American Association for the Advancement of Science

Southwestern Division

Program of Section C

Tuesday Session, December 30, 9:00 A.M.; Baker Hotel, Dallas, Texas

Edward A. Doisy, *Chairman*

1. Introductory Remarks. William M. Craig, *Texas Technological College, Lubbock, Texas.*

2. Spectrochemical Analysis in the Iron and Steel Industries. Ralph A. Sawyer, *University of Michigan, Ann Arbor, Michigan.*

3. Spectroscopic Sources Used in Spectrochemical Analysis. Ora Stanley Duffendack, *University of Michigan, Ann Arbor, Michigan.*

4. Spectrographic Analysis in Industry. J. L. Saunderson, *Dow Chemical Company, Midland, Michigan.*

5. Quantitative Spectrochemical Methods for Non-Metallic Analysis. Maurice F. Hasler, *Applied Research Laboratories, Los Angeles, California.*

6. Ultraviolet Absorption and Resonance in Organic Molecules. W. H. Rodebush, *University of Illinois, Urbana, Illinois.*

7. Gas Analysis with the Mass-Spectrometer. John A. Hipple, Jr., *Westinghouse Research Laboratories, Pittsburgh, Pennsylvania.*

8. Applications of Infra-Red Spectroscopy to Chemical Research. Henry R. Kreider, *Chemical Laboratory, American Medical Association, Chicago, Illinois.*

9. The Spectrum of the Night Sky. C. T. Elvey, *McDonald Observatory, Fort Davis, Texas.*

10. The Chemical Analysis of the Stars. Franklin E. Roach, *University of Arizona, Tucson, Arizona.*

11. Some Characteristics of the Photoelectric Spectrophotometer. Marshall N. States, *Research and Development, Central Scientific Company, Chicago, Illinois.*

Spectrochemical Determination of Trace Metals in Biological Material*

JACOB CHOLAK AND ROBERT V. STORY
Kettering Laboratory of Applied Physiology, College of Medicine, University of Cincinnati, Cincinnati, Ohio
(Received August 27, 1941)

THE application of emission spectrography to quantitative analysis is based on a number of well-recognized principles and procedures with certain technical adaptations for specific purposes. In many instances, particularly in metallurgical investigations, the material handled is of a relatively simple and constant nature, requiring little, if any, chemical preparation. Moreover, the concentrations dealt with are seldom below 0.001 percent and the analyst is therefore offered a considerable latitude in choice of procedure. In contrast, biological specimens as received are rarely suitable for direct analysis, requiring as a rule chemical pretreatment; the ash matrices vary widely and for certain materials show considerable change from day to day, and in addition, metals must often be determined in the range of 0.0001–0.00001 percent or less, by weight of fresh material, since in many cases variations in this range are of physiological importance. It is obvious, therefore, that if the conclusions drawn from spectrochemical analysis of biological material are to be given any credence, the method employed must be adequate in respect to specificity, sensitivity, and accuracy. It is not possible to follow set rules of procedure for development of suitable methods, but it is the purpose of this paper to discuss a number of the factors involved.

THE INSTRUMENT

The spectrograph employed should have a sufficient dispersion to prevent the masking of analytically important spectrum lines. Many of these lines occur in the ultraviolet region and therefore prism spectrographs should also possess quartz optical systems and trains. Dispersions equal to that given by the Bausch and Lomb large quartz Littrow-type spectrograph (1.9A per mm at 2300A to 7.1A per mm at 3550A) are required to permit the use of any of the lines listed in Table I, especially with the wide slits (0.02–0.05 mm) commonly used in quantitative methods. These lines are essential for the determination of traces of these metals since other characteristic lines, except those for aluminum and tin, occur only at higher concentration levels. Masking of the aluminum line at 3082.2A by the cobalt line at 3082.6A is not likely to occur in natural material, but it has been included because cobalt is used as an internal standard in the analysis of aluminum.[1] The usefulness of instruments of smaller dispersion is much more limited since chemical separations would be needed in many instances to remove interfering elements. Such procedures are not recommended except when absolutely essential, for the increased manipulations tend to invalidate the specificity of the detection and also offer opportunities for contamination and loss.

SPECTRAL SOURCES

The concentration of the test metal governs the choice of spectral source and when sufficiently high, any of the conventional sources or their variations[2–17] will be found satisfactory. As the

TABLE I. *Analytically important spectrum lines and possible masking lines.*

ELEMENT	WAVE-LENGTH	WAVE-LENGTH AND NATURE OF MASKING LINE	
Mercury	2536.5	2535.65	Phosphorus
Antimony	2598.1	2598.4	Iron
Thallium	2767.9	2767.5	Iron
Arsenic	2780.2	2779.85	Magnesium
Lead	2833.07	2832.4	Iron
Tin	2840.0	2840.4	Iron
Bismuth	3067.7	3067.2	Iron
		3068.2	Iron
Aluminum	3082.2	3082.6	Cobalt
Cadmium	3261.05	3262.3	Tin

* Presented in part at the Second Midwest Conference on Spectrographic Analysis at the University of Chicago, March 29, 1941.

[1] J. Cholak and R. V. Story, Ind. Eng. Chem. Anal. Ed. **10**, 619 (1938).
[2] E. Baum, Ann. d. Physik **34**, 377 (1939).
[3] O. S. Duffendack and K. B. Thomson, Proc. A. S. T. M. **36**, (II) 301 (1936).
[4] J. S. Foster and C. A. Horton, Proc. Roy. Soc. **B123**, 422 (1937).
[5] W. Gerlach and E. Gerlach, *Foundations and Methods of Chemical Analysis by the Emission Spectrum (1929);*

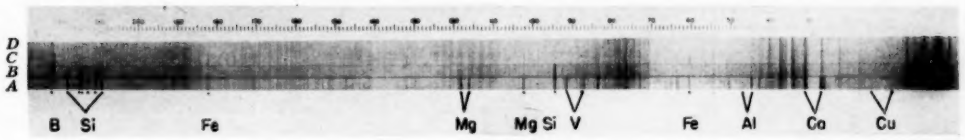

FIG. 1. Spectra of various graphite electrodes (2495A–3500A). *A*—graphite electrodes (Acheson); *B*—same as *A* following chemical purification; *C*—Dow purified electrodes; *D*—same as *C* following MeOH treatment.

concentration of the test metal decreases, the choice becomes limited until finally, in the case of traces of metal, only the arc across graphite electrodes is suitable. Various types of arcs have been used,[1,3,8,10,12,14,18] but certain advantages over the direct current arc, claimed for a number of them, are offset either by inferior sensitivity, lack of convenience, or the need for extra, complicated apparatus. The "cathode-layer" arc[12,19] has been recognized as the most sensitive source, but the increased sensitivity is not of practical quantitative significance. Another source, the high voltage alternating-current arc,[3,14,18] is ideal for many purposes but its reported sensitivity for biological or organic material[14,20] is not superior to that of the d.c. arc, as may be seen by comparison with the data given in Table II, and in addition, the periods of exposure which are required, especially for the detection of traces in biological material,[21] are several times longer than those employed in the case of the d.c. arc.[1]

One difficulty common to the use of graphite electrodes has to do with their purity. Spectroscopic graphite electrodes as purchased may be used for the detection of many metals present in traces and for others which are present in quantitatively insignificant proportions in the electrodes. Whenever the most persistent line must be used, it is desirable that the element in question be absent from the electrodes. Very pure electrodes can be purchased, but satisfactory electrodes may be prepared at far less expense by extracting the properly cut rods for several days with a mixture of acids in a Soxhlet apparatus and then washing or extracting them with distilled water,[1] a treatment which removes practi-

TABLE II. *Persistent lines and sensitivities. (10 amp.–60 v drop from 110 v d.c. line.) (Positive crater = 10 mm deep, cathode = pointed in pencil sharpener.)*

ELEMENT	WAVE-LENGTH	SENSITIVITY MG ON ELECTRODE
Aluminum	3082.16	2×10^{-5}
Antimony	2598.1	4×10^{-4}
Arsenic	2780.2	1×10^{-3}
Bismuth	3067.7	2×10^{-5}
Cadmium	3261.1	4×10^{-4}
Chromium	2986.0	2×10^{-4}
	2835.6	5×10^{-4}
Copper	3274.0	2×10^{-5}
Iron	3020.7	2×10^{-5}
Lead	2833.07	2×10^{-5}
Magnesium	2852.1	1×10^{-5}
	2802.7	2×10^{-5}
Manganese	2801.1	2×10^{-5}
Mercury	2536.5	2×10^{-4}
Nickel	3050.8	4×10^{-4}
Phosphorus	2535.6	5×10^{-3}
Silicon	2881.0	2×10^{-4}
Silver	3280.7	1×10^{-5}
Sodium	3302.0	2×10^{-3}
Thallium	2767.9	2×10^{-5}
Tin	2840.0, 3175.1	2×10^{-5}
Zinc	3302.6, 3345.0	2×10^{-3}

Clinical and Pathological Applications of Spectrum Analysis, (Adam Hilger, London, 1934).

[6] W. Gerlach and W. Rollwagen, Metallwirtschaft **16**, 1083 (1937).

[7] W. Gerlach, W. Rollwagen and R. Intonti, Arch. path. Anat. (Virchow's) (III) **301**, 588 (1938).

[8] W. Gerlach, Spectrochim. Acta **1**, 168 (1939).

[9] R. J. Keirs and D. T. Englis, Ind. Eng. Chem. Anal. Ed. **12**, 275 (1940).

[10] H. Lundegardh, *Die quantitative Spektralanalyse der Elemente* I (1929); II (Gustav Fischer, Jena, 1934); Lantbruks-Högskol Ann. **3**, 49 (1936); H. Lundegardh and T. Philipson, Lantbruks-Högskol Ann. **5**, 249 (1938).

[11] F. Majewsky, Nature **144**, 1047 (1939).

[12] R. Mannkopff and C. Peters, Zeits. f. Physik **70**, 444 (1931).

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[14] J. S. Owens, Metals and Alloys **9**, 15 (1938); Ind. Eng. Chem. Anal. Ed. **11**, 59 (1939).

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[16] G. Scheibe and J. Martin, Spectrochim. Acta **1**, 47 (1939).

[17] F. Twyman and C. S. Hitchen, Proc. Roy. Soc. **A133**, 72 (1931).

[18] A. E. Ruehle and E. K. Jaycox, Ind. Eng. Chem. Anal. Ed. **12**, 260 (1940).

[19] L. W. Strock, *Spectrum Analysis with the Carbon Arc Cathode Layer* (Adam Hilger, London, 1936).

[20] T. M. Hess, J. S. Owens and L. G. Reinhardt, Ind. Eng. Chem. Anal. Ed. **11**, 646 (1939).

[21] R. A. Sawyer, R. W. Waggoner and A. A. Erickson, *Proceedings Seventh Summer Conference on Spectroscopy and Its Applications* (John Wiley and Sons, New York, 1940), p. 47.

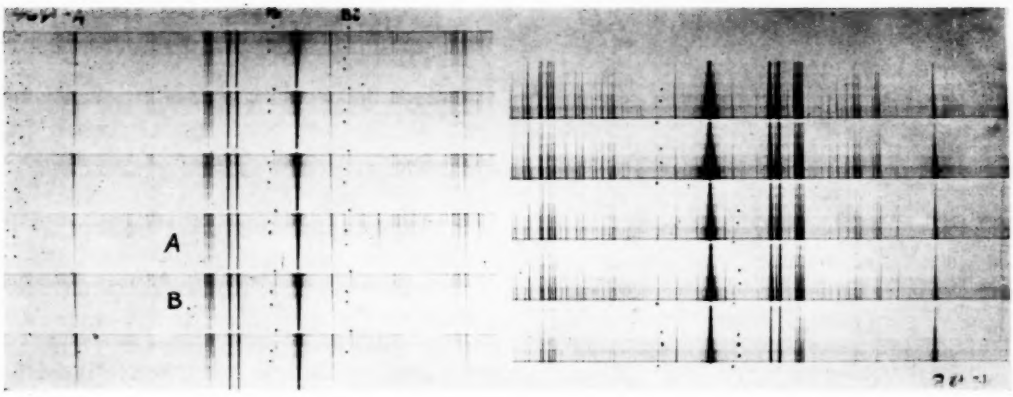

FIG. 2. Typical work plate obtained with step sector and mask.

cally all impurities except boron and silicon. These rods are inferior to the more expensive Dow purified electrodes only in that the latter are free from silicon. Methods of purification thus far described[1, 6, 10, 14, 22, 23] do not remove boron and in some cases even increase its amount. It was hoped that refluxing with acidified methyl alcohol, which is effective in removing boron from plant ash,[24, 25] would also remove it from electrodes, but the result of this procedure, as shown in Fig. 1, was disappointing. As in the case of silicon, special electrodes (special carbon spectroscopic electrodes, National Carbon Company) must be used for the analysis of boron. The data of Fig. 1 also show a somewhat higher content of iron and magnesium in the Dow purified electrodes than in those purified by means of acid extraction. Since the chemically purified electrodes have been cut and shaped before purification, chances for contamination from handling are less, and therefore we prefer them for all analyses except those for boron and silicon. Metal electrodes may also be used but these are not as satisfactory as graphite because of the inconvenience of cleaning them and also because the temperatures obtained are not high enough for the detection of the smaller traces of impurities.

[22] G. Heyne, Zeits. f. angew. Chemie **45**, 612 (1932).
[23] Th. Zürrer and W. D. Treadwell, Helv. Chim. Acta **18**, 1181 (1935).
[24] J. S. McHargue and R. K. Calfee, Ind. Eng. Chem. Anal. Ed. **4**, 385 (1932).
[25] K. L. Robinson, Analyst **64**, 324 (1939).

DENSITOMETRY

The methods of densitometry in common use[1, 5, 10, 17, 19, 21, 26–31] are applicable to biological material. In order to take advantage of the linear response of the photographic plate over a wider range of working conditions than is the usual practice, we have made use of both density-exposure and opacity-exposure data.[1, 32] The former are used when conditions are favorable for the application of the straight line portion of the characteristic D-log E curve for the plate, while the latter take advantage of the fact that photographic blackenings in the under-exposed portion of the plate have an approximate linear relation to the exposure.[10] This modification, an adaptation of Lundegardh's L/H method,[10] is of great value, especially in examining normal material, in which case it is preferable to measure the weak lines obtained rather than to run the risk of possible losses and contamination in further manipulations designed to permit the use of more favorable D-log E data.[1, 32]

[26] O. S. Duffendack, R. A. Wolfe and R. W. Smith, Ind. Eng. Chem. Anal. Ed. **5**, 226 (1933).
[27] F. Eisenlohr and K. Alexy, Zeits. f. physik. Chemie **A179**, 241 (1937).
[28] S. Judd Lewis, Chem. and Ind. **51**, 271 (1932).
[29] C. C. Nitchie and G. W. Standen, Ind. Eng. Chem. Anal. Ed. **4**, 182 (1932).
[30] G. Scheibe and A. Neuhäusser, Zeits. f. angew. Chemie **41**, 1218 (1928).
[31] F. Twyman, *Spectrochemical Analysis in 1938* (Adam Hilger, London, 1938); F. Twyman, G. F. Lothian and E. S. Dreblow, J. Soc. Chem. Ind. **57**, 75 (1938).
[32] J. Cholak, Ind. Eng. Chem. Anal. Ed. **7**, 287 (1935); **9**, 26 (1937).

When an internal standard is used, the greatest accuracy and flexibility of application can be secured by using the step sector[1,19] for each analytical spectrum. This procedure places the calibration mark in each spectrogram and makes the analytical range of a line considerably greater than is possible when the same line is used in unstepped spectra. Its use requires an increased number of densitometric readings and is not economical of plate space, but the increased flexibility and accuracy are worth the extra time and plates. In many instances a judicious choice of spectrograph setting plus a suitable mask[33] will provide twice the usual number of spectrograms on a plate (see Fig. 2; step factor = 2). The length of the spectrograph slit used and the number of spectra which can be taken on a plate depend on the size of the step which can be measured in the densitometer. In the case illustrated, 2.5 mm steps were required, and for a 5 step sector, the plate was moved 14 mm for each spectrum.

In practice, the application of D-log E data is similar to that described by Strock[19] in which the relative log E separations between the D curves for the test and standard lines, at a constant equal density ($D = 0.30$) are correlated against the log concentrations of the test metal. If the density of a line in the step of maximum exposure is less than 0.20, more satisfactory results can be obtained by employing data on opacities. The procedure here is similar to that involved in dealing with densities except that opacities in only two consecutive steps are noted and these are plotted against the corresponding relative exposures. If possible, the steps chosen should give opacities on either side of the base or equal opacity level (1.30) and the maximum should not greatly exceed 1.50, since above this value the opacity curve rapidly becomes parallel to the exposure axis. This requirement necessitates a judicious choice of the quantity of internal standard to be added; it should be such that measurements of either opacity or density can be employed, depending on the reaction of the test line. If the test line is present only in the maximum exposure step, the plot is made by using an opacity of 1 in the next lower step.[1] The two methods are illustrated in Fig. 3, in which some of the spectra in Fig. 2 have been employed. Correlation of the measurements with concentration, and the ranges and limits of the two procedures for a number of spectral lines are shown in Figs. 4 and 5.

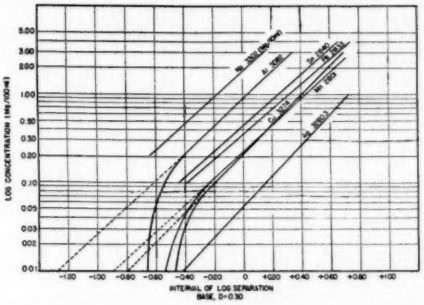

FIG. 4. Calibration curves based on D-log E data.

A number of changes in the Bausch and Lomb density comparator have simplified the above procedure for evaluating the photographic data. The changes were made somewhat along the lines suggested by Scribner[34] in order that galvanometer deflections could be used directly in place of the calculated opacities or densities. The Weston Photronic cell has been replaced by a G. E. light-sensitive cell and the maximum galvanometer deflections are kept at a constant value by means of a Type 200-CM "Variac" autotransformer in series with the light source. The original 0–380 mm scale has been replaced by a new scale, approximately the same length divided into 100 units, so that when the constant deflection is set by means of the Variac at 100 through a clear portion of the plate, the deflection through the spectrum lines will give relative transmittancies.

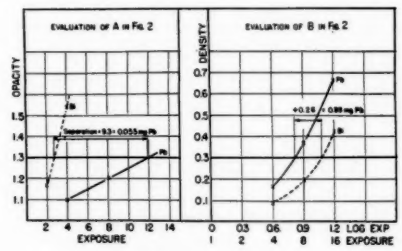

FIG. 3.

[33] G. Bolz, Spectrochim. Acta **1**, 227 (1939).

[34] B. F. Scribner, *Proceedings of Fifth Summer Conference on Spectroscopy and Its Applications* (John Wiley and Sons, New York, 1938), p. 51.

In practice the transmittancies are used directly, the separations being taken at a T value of 0.50 corresponding to the $D=0.30$ of B in Fig. 3. In dealing with the very weak lines (opacity technique), since one is dealing essentially with straight line intercepts, a table has been drawn up from which the intercepts of the plots for test and internal standard lines with the T value of 0.77 (opacity of 1.30) may be taken.[35] In making this table the transmittancies for the maximum exposure step (arbitrarily assigned a value of 8) and the next lower step (exposure 4) have been used. The formula employed was

$$\text{intercept}=4\left(1+\frac{77-x}{y-x}\right),$$

where x and y are the galvanometer readings for the lower and higher steps, respectively. If the measurements are made with exposure steps 4 and 2 the value from the table must be divided by 2 and if 2 and 1 steps are used, it must be divided by 4.

In evaluating densitometer readings, the effect of background is a source of difficulty which cannot be corrected for in any simple manner.[19,31] If the conditions of spectrographic procedure are strictly standardized and rigidly maintained, it is possible to obtain spectra which show only slight variations in background fog and, therefore, corrections for its effect may be neglected,[19,31] or other empirical working curves may be obtained along the lines described by Lundegardh.[10] Under the conditions of procedure as outlined in this paper, background densities greater than 0.10 in the maximum exposure step are rarely obtained except in the region above 3000A. Important lines of Al, Cu, Sn, or Ag in this region are very persistent and it is possible to reduce the background markedly, without materially reducing the sensitivity of detection, by introducing a rotating sector in front of the step sector.

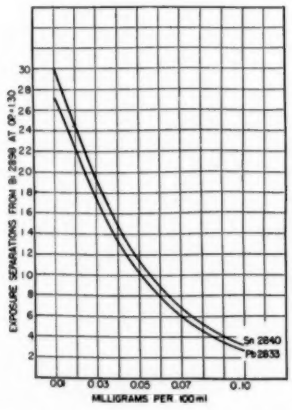

FIG. 5. Calibration curves based on opacity-exposure data.

CALIBRATION CURVES

In a number of instances working curves can be developed for individual materials merely by adding the test metal and internal standard to the normal material, but frequently, because of the wide distribution of certain metals, it is necessary to employ purified synthetic bases. In order to use a single curve applicable to all materials, and also to reduce the effect of extraneous ions on line intensities, the base should conform within reasonable limits to the inorganic salt composition of the test material. A synthetic urine-ash solution[1,32] makes a suitable base, and for practical use its inorganic salt concentration should be ten times that of an equal volume of normal urine. By mixing such a solution (in which the inorganic salts are those common to biological ash but are present in large excess) with an equal part of a solution of ashed sample (the volume of which is adjusted so that 1 ml corresponds to 1 g of fresh tissue), it is possible to obtain a test solution conforming closely with the base used to derive the working curves.[1,32] This is usually done with all materials except urine.

The chief difficulty in the use of synthetic spectroscopic bases arises from the need of purifying them. Most troublesome impurities are manganese, lead, copper, zinc, aluminum, iron, and silicon. It is possible to remove practically all of the lead and copper,[1] and zinc can be removed by treatment with dithizone,[36] but thus far we have not been able to remove manganese, aluminum, iron, and silicon. Therefore results have to be corrected for the amounts of these metals present in the base. The degree of constant contamination is determined from the amount of

[35] P. Oesper, private communication.

[36] H. Fischer, Zeits. f. angew. Chemie **50**, 919 (1937).

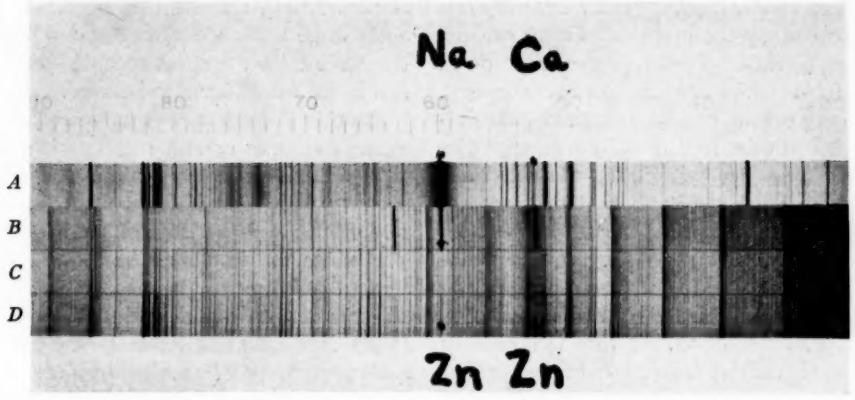

FIG. 6. Showing masking of zinc lines and identification following dithizone extraction. *A*—spectroscopic base; *B*—pure zinc solution; *C*—acid washing of dithizone extract of spectroscopic base; *D*—similar to "*C*" but containing zinc (5 micrograms on arc).

deviation of the curved portions from the extrapolated straight line sections indicated by the dotted lines in Fig. 4. (The source of contamination in the case of the copper curve is the internal standard from which we have not succeeded in removing it.[1]) Inability to remove these metals forces the analyst to check the lower portions of the calibration curves each time the base solution is made up from a fresh batch of chemicals.

PREPARATION OF SAMPLES

A complete understanding of all factors involved in the chemical preparation of samples is as essential in spectrochemical analysis of biological material as is a proper understanding of the spectrographic technique. Needless to say, the chemical processes employed must be precise and every detail of sample collection and preparation must be carefully controlled and studied to prevent undue losses or contaminations. Since each metal constitutes a distinct problem, a set procedure cannot be established, and consequently it is not possible to determine more than a few metals simultaneously by means of a single spectrogram.

Experience has shown that manganese, lead, tin, aluminum, copper, silver, iron, and thallium among others can be determined from the same spectrogram of ashed samples.[1] All have very sensitive lines with practically the same ultimate sensitivity, and in each case a dry ashing technique (500°C) can be employed without causing losses of the metals. With a suitable spectroscopic buffer, magnesium, sodium, and calcium, when present in small amounts, can also be included in the above list. Usually, however, they are present in such quantities that with the arc method of excitation, the dilution required to give satisfactory analytical ranges with certain lines would prevent the detection of traces of other metals. In all such cases, it is unnecessary to concentrate the samples greatly.

Small amounts of certain other metals can be determined only after concentration; examples are cadmium, antimony, mercury, arsenic, chromium, zinc, and nickel. Certain of them, particularly mercury and arsenic, also require special methods for the destruction of organic matter in order to prevent losses by volatilization.[37,38] Concentration by evaporation to small volumes is frequently not sufficient, especially in the presence of large excesses of extraneous ions, and chemical separation must also be employed. Treatment with hydrogen sulfide and subsequent concentration of the dissolved metal sulfide is often a satisfactory procedure,[32] and electrolytic

[37] E. Kahane and M. Pourtoy, J. pharm. et chim. [8], **23**, 5 (1936).

[38] K. O. Møller, Biochem. Zeits. **223**, 379 (1930).

methods can also be used,[39–41] but frequently it is possible to employ the more convenient organic complexing agents.[36] Under proper conditions, very small quantities of cadmium and mercury, among many others, can be extracted quantitatively with dithizone[36] or di-β-naphthylthiocarbazone.[42] The spectrograph has not been used extensively for the determination of traces of arsenic, but the development of methods in which arsenic is distilled as $AsCl_3$[43] suggests the possibility of concentrating the arsenic sufficiently to permit the determination of quantities as low as 0.005 mg per ml solution. All that is necessary is to evaporate the $AsCl_3$ distillate to a volume of 1 ml, which can be made to contain the internal standard base, and then to arc 0.2-ml portions. Since large amounts of magnesium would mask the arsenic line, a spectroscopic base free from this metal would have to be used.

TABLE III. *Comparison of spectrographic[a] and dithizone[b] lead determination on consecutive weekly blood samples during experimental study on two subjects.*

	M. R. Frequencies		E. B. Frequencies	
Mg Pb/100 g	Spectrographic	Dithizone	Spectrographic	Dithizone
0.0250–0.0299			5	3
0.0300–0.0349	3	1	0	2
0.0350–0.0399	12	3	7	5
0.0400–0.0449	26	6	8	3
0.0450–0.0499	25	16	4	9
0.0500–0.0549	24	38	17	10
0.0550–0.0599	19	31	16	15
0.0600–0.0649	20	24	22	24
0.0650–0.0699	13	14	4	12
0.0700–0.0749	8	16	5	12
0.0750–0.0799	3	4	5	3
0.0800–0.0849	1	0	8	5
0.0850–0.0899	0	2	1	
0.0900–0.0949	0	0	1	
0.0950–0.0999	0	1		
0.1000–0.1049	2	0		
Total	156	156	103	103
Mean	0.054	0.058	0.058	0.059
Probable Error	±0.001	±0.001	±0.001	±0.001
Standard Deviation	±0.012	±0.010	±0.014	±0.013
Coefficient of Variability	±23%	±17%	±25%	±21%
Median	0.053	0.057	0.058	0.061
Mode	0.051	0.055	0.058	0.065

[a] See reference 1 in text.
[b] See reference 45 in text.

Another class of metals may require chemical separation from certain matrices in spite of its high sensitivity of detection. An example is bismuth, which is quite difficult to detect in small amounts in the presence of large quantities of iron, since the iron lines at 3067.2 and 3068.2 mask the bismuth line at 3067.7A.[32] Another example is to be found in zinc. The zinc lines at 3302A and 3345A, suitable in the range above 0.001 percent may be masked respectively by Na and Ca lines. In this case it is possible to determine small quantities of zinc satisfactorily, if the metal is removed from the extraneous material by dithizone extraction.[36] Figure 6 shows the masking of the zinc lines and the possibility of effective detection following suitable extraction techniques.

In order to guarantee the homogeneous nature of the test sample and to facilitate the handling of the small quantities of material used in a quantitative test, it is preferable to work with solutions. In qualitative studies the dry ashed material should be used directly, when possible, to avoid possible slight contaminations which, while quantitatively insignificant, may give rise to misleading conclusions as to the presence or absence of certain metals.

Sensitivities and Accuracy of Analysis

In Table II are listed spectral lines and quantities of metals which must be present in the arc to permit quantitative analysis at the lower range limits. In most cases the ultimate sensitivities are represented by even lower values. Many of the lines listed are the most persistent lines, while in other cases lines are given which are satisfactory either after concentration of the test metal, or when higher quantities of the metal are to be determined. In the case of zinc, the line most suitable for the detection of traces is that at 2138.5A, but it can be photographed only on a specially sensitized plate.[44]

If satisfactory chemical procedures are em-

[39] E. Bayle and L. Amy, Comptes rendus **185**, 268 (1927); Bull. Soc. Chim. **43**, 604 (1928).
[40] W. Gerlach and E. Schweitzer, Zeits. f. anorg. u. allgem. Chemie **195**, 255 (1931).
[41] C. Sannie and V. Poremski, Bull. Soc. Chim. d. France **6**, 1401 (1939).
[42] D. M. Hubbard, Ind. Eng. Chem. Anal. Ed. **12**, 768 (1940).
[43] J. A. Scherrer, J. Research Nat. Bur. Stand. **16**, 253 (1936).
[44] L. H. Rogers and O. E. Gall, Ind. Eng. Chem. Anal. Ed. **9**, 42 (1937).

TABLE IV. *Comparative lead findings on biological material.*

MATERIAL	GRAMS	SPECTROGRAPHIC[a]	DITHIZONE[b]	POLAROGRAPHIC[c]
		MG LEAD PER 100 GRAMS		
Spleen	28.4	1.05	1.18	1.11
Heart	30.1	0.05	0.03	0.040
Suprarenal	6.0	0.24	——	0.20
Stomach	26.5	0.085	0.095	0.075
Lung	49.0	0.39	0.40	0.36
Muscle	29.0	0.045	0.03	0.030
Thyroid	4.5	0.62	——	0.57
Rib bone	6.5	16.85	17.7	17.1
Blood	20.0	0.075	0.071	0.071
		MG LEAD PER LITER		
Urine	100 ml aliquots	0.043	0.038	0.036
Urine	100 ml aliquots	0.17	0.17	0.165
		MG LEAD PER 24 HOURS		
Feces	0.10–0.15 g ash (aliquots)	0.32	0.30	0.29
Food	1/20th day's food (aliquot)	0.22	0.22	0.21

[a] See reference 1 in text.
[b] See reference 45 in text.
[c] See reference 46 in text.

TABLE V. *The concentrations of trace metals in normal blood.*

WHOLE BLOOD MG PER 100 G	Mn	Pb	Sn	Al	Cu	Ag
Mexicans:						
Mean	0.018	0.023	0.010	0.012	0.126	Trace
Probable error	±0.001	±0.00005	±0.0015	±0.001	±0.002	
Standard deviation	±0.010	±0.004	±0.012	±0.010	±0.018	
Americans:						
Mean	0.012	0.027	0.014	0.014	0.103	Trace
Probable error	±0.001	±0.0006	±0.0015	±0.002	±0.002	
Standard deviation	±0.006	±0.005	±0.012	±0.012	±0.013	
Whole group:						
Mean	0.015	0.025	0.012	0.013	0.114	Trace
Probable error	±0.001	±0.0004	±0.0009	±0.001	±0.002	
Standard deviation	±0.009	±0.005	±0.010	±0.011	±0.020	
Distribution in plasma (Americans)[a]						
Plasma:						
Mean	0.004	0.0015	0.002	0.024	0.043	
Probable error	±0.0005	±0.0002	±0.0002	±0.002	±0.0015	
Standard deviation	±0.003	±0.0013	±0.0014	±0.012	±0.012	

[a] Based on 100 g of whole blood.

ployed in the preparatory steps, the error in spectrochemical analysis of traces varies with the range of concentrations dealt with. Under favorable conditions it may be expected to be no greater than ±5 or 10 percent. Under certain conditions the error, expressed as an ultimate value, may be almost unbelievably small, but when calculated on the basis of the quantities handled the percentage error becomes large. This is clearly illustrated by our report of a method for the spectrochemical determination of lead in biological material in which a sensitivity of detection of ±0.02 microgram on the arc is claimed.[32] With the dilution of sample employed in that method, errors of the above magnitude occurring in the estimation of lead in the aliquots arced give percentage errors varying from ±100 percent in the case of samples in which the lead content is 0.01 mg per liter or per 100 g of fresh tissue, to ±10 percent when the amount reaches 0.10 mg per liter or per 100 g of sample. Above the value of 0.10 mg, the over-all error may well be expressed as ±10 percent, and in fact the error of analysis may frequently be only 5 percent, especially if the range involved permits measurement of line densities which fall on the

segment representing the lower two-thirds of the straight-line portion of the characteristic D-log E curve for the plate. The greater errors observed for the lower levels do not indicate that the method is inferior to chemical methods, since the latter often show the same increase in error at these levels.

A further proof of the accuracy of spectrochemical analysis may be gained by comparison of results with those obtained by chemical methods. Such a comparison is given in Table III, in which data are recorded for the determination of lead in consecutive duplicate blood samples from two subjects under experimental study. The essential correspondence of the two sets of results, with respect to the frequencies of occurrence and the range of variability of the analytical results, as well as the mean values, shows that the spectrographic method is as accurate as the dithizone method. Further comparisons are shown in Table IV, where the lead values obtained by spectrographic determination for a number of materials are compared with the dithizone[45] and polarographic[46] findings. Aliquots from the same prepared sample were employed and the results frequently agreed within 1 microgram of lead.

Although we have not found it possible as yet to make extensive comparative studies on other metals, our findings for the concentrations of several of them in normal biological material[47] compare favorably with values determined by chemical means[47] as reported by others. Table V lists results for a number of metals determined simultaneously in a single prepared sample (10 g) of normal blood. The data illustrate a useful application of spectrochemical analysis.

[45] K. Bambach, Ind. Eng. Chem. Anal. Ed. **11**, 400 (1939).
[46] J. Cholak and K. Bambach, Ind. Eng. Chem. Anal. Ed. **13**, 583 (1941).
[47] R. A. Kehoe, J. Cholak and R. V. Story, J. Nutrition **19**, 579 (1940); **20**, 85 (1940).

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A Low Brightness Meter

A. H. TAYLOR
Lighting Research Laboratory, General Electric Company, Nela Park, Cleveland, Ohio
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IN the measurement of low brightnesses outdoors at night, in areas without artificial light, instruments and methods satisfactory at higher brightness levels are no longer satisfactory. With the Luckiesh-Taylor Brightness Meter[1] it is possible to measure brightnesses as low as 0.0025 footlambert, but outdoor brightnesses at night may be only a hundredth of this value.

At these low brightness levels it is difficult even to locate a photometric field through a small artificial pupil, such as is necessary if lenses are used. The natural diameter of the pupil of a thoroughly dark-adapted eye may be as much as eight millimeters, hence the use of an artificial pupil three millimeters in diameter results in the loss of 85 to 90 percent of the light. Furthermore, the use of any lenses results in still further loss. These considerations lead to the conclusion that a satisfactory low brightness meter should contain no lenses and should not have an artificial pupil to limit the light received by the eye. Obviously, long adaptation of the observer's eyes is necessary for accurate measurements.

The author has recently developed a low brightness meter involving these principles and with it has made measurements as low as 0.000025 footlambert. The meter is illustrated in Fig. 1. The shielded headrest serves to locate the eye centrally in front of a hole about an inch in diameter on the axis of a tube 23 inches long and $2\frac{3}{4}$ inches in diameter. This tube is lined with black velvet. A few inches from the opposite end of the tube is located a short side tube at right

[1] M. Luckiesh and A. H. Taylor, J. Opt. Soc. Am. **27**, 132 (1937); Trans. I. E. S. **32**, 235 (1937).

angles to the long tube. At the outer end of the side tube is a small flashlight lamp. About 2 inches from the outer end of this tube is an opaque diaphragm with a $\frac{1}{8}$-inch hole through which the light from the lamp shines onto a circular photographic gradient and light diffuser. The gradient and diffuser are mounted so they can be rotated about the axis of the gradient, thus varying the amount of light incident on a translucent opal glass located at the intersection of the tubes. A strip of mirror approximately $\frac{1}{2}$-inch wide is placed at 45 degrees in the longer tube and produces an image of the opal glass at a distance of approximately 21 inches from the eye. Either of two neutral filters, transmission ten and one percent, may be placed in the path of the comparison beam by means of the small knob seen near the gradient.

When making a measurement the observer places his forehead against the headrest and views the test field through the long tube. The brightness of the comparison field, seen in the 45-degree mirror, is then adjusted in brightness by means of the photographic gradient and neutral filters until it blends into the test field. Since visual acuity is low at these brightness levels, accurate focus is not essential. Furthermore, there is little or no trouble due to color difference. At very low brightness levels increased sensitivity may be obtained by use of peripheral vision. The black velvet lining of the tube increases the ease of measurement by blotting out everything except the photometric field.

It is customary to assume that the unit of brightness has a fixed value in terms of energy-density of the stimulus, regardless of the spectral distribution of the radiant energy from the light-source.[2] This assumption is probably a safe

[2] Matthew Luckiesh and A. H. Taylor, "Tungsten, mercury and sodium illuminants at low brightness levels," J. Opt. Soc. Am. **28**, 237 (July, 1938).

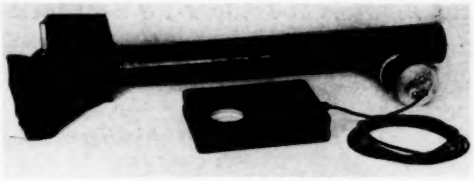

FIG. 1.

one for brightnesses above 0.1 footlambert, but for brightnesses below this value the relationship between the stimulus (energy) and the brightness sensation produced is no longer constant, owing to the Purkinje effect, if lights differing appreciably in spectral energy distribution are being measured. In calibrating the meter the starting point was a brightness of several footlamberts produced by light from a tungsten-filament lamp incident on translucent opal glass viewed from the opposite side. The brightness of the opal glass was varied by varying the distance of the lamp and by interposition of rotating sectored disks. The transmissions of the neutral filters had been measured at higher brightness levels before use in this meter.

The brightness range of the first meter constructed was 0.05 to 0.000014 footlambert. Another meter of the same type has a range of 0.012 to 0.000006 footlambert and there would be no difficulty in producing a meter for still lower brightnesses, if it is possible to see well enough to make measurements at such very low levels.* As previously stated, measurements as low as 0.000025 footlambert were made with this instrument; and it would probably have been possible to go still lower had it been desirable.

It may be of interest to note that the brightness of the zenith sky on a clear moonless night was found to be approximately 0.00015 footlambert.

* The brightness range of the latest meters has been extended and is now 0.1 to 0.000005 footlambert.

The Analysis of Toluene for Benzene by an Ultraviolet Absorption of Vapor Mixtures and the Determination of Concentration of Toluene in Air by Use of the Rayleigh-Jeans Interference Refractometer*

P. A. Cole and D. W. Armstrong
Division of Industrial Hygiene, National Institute of Health, Bethesda, Maryland

A quantitative spectrographic method for the analysis of toluene for benzene is described, which is useful in the range of concentrations of benzene from 0.01 to 10 percent. The method is both convenient and highly specific. The use of the Rayleigh-Jeans interference refractometer in the control of concentration of toluene vapor in an exposure chamber suitable for toxicological investigations is described. The method employed is both rapid and accurate. At low concentrations, with the bubbler used, the control is within 5 percent of the amount present; at higher concentrations the control is within 10 percent.

Introduction

THE use of toluene has increased greatly because of the National Defense Program, both in the manufacture of TNT and as a solvent in many industries. This investigation is part of a study concerning the toxicity of toluene vapor now being carried out by the Division of Industrial Hygiene of the National Institute of Health. For this purpose it was highly desirable to use toluene of tested purity, particularly free of benzene. This was effected by means of a spectrographic method which determined quantitatively the amount of benzene present by the ultraviolet absorption spectra of vapor mixtures. It was also desirable to possess a ready and reliable means of estimation of the concentration of toluene vapor present in a suitable experimental chamber. No practical chemical method existed. The use of the Rayleigh-Jeans interference refractometer was suggested, and in practice was found to be quite satisfactory. The spectrographic analytical method will be discussed first. This will be followed by a description of the installation of the Rayleigh-Jeans interference refractometer.

Analysis by Ultraviolet Absorption

The analysis of toluene for benzene has been accomplished by many methods. These depend on physical properties of the mixture, such as boiling point,[1] critical temperature,[2] miscibility with water alcohol mixtures,[3] or distillation of the material and subsequent chemical examination of the fractions by colorimetric methods.[4] All of these methods have the difficulty of being non-specific and some of them have a low sensitivity in comparison to the method presented here.

Ultraviolet spectroscopic examination of solutions of benzene and toluene is efficient and desirable at low concentrations of toluene[5] but in the range under consideration (0.01 to 10 percent benzene) this method is useless, due to overlapping of the bands. In order to overcome this difficulty ultraviolet absorption of the vapor mixtures of these substances was studied. The absorption spectrum of benzene vapor has been studied extensively by many workers, most notably by V. Henri[6] who suggested the possibility of the analytical method employed here. More recently, the benzene spectrum has been studied by Sponer, Nordheim, Sklar and Teller, also Radle and Beck.[7] The data on toluene, however, is much more limited.[8]

* Presented at the Ninth Summer Conference on Spectroscopy and Its Applications at the Massachusetts Institute of Technology, Cambridge, Massachusetts, July 21–23, 1941.

[1] S. Nemura and Y. Kosaka, J. Soc. Chem. Ind. Japan **32**, 279 (1929).
[2] J. Harand, Monats. f. Chemie **65**, 153 (1935).
[3] K. Hradsky, Chem. Obzor. **11**, 120 (1936).
[4] S. Pearce, H. Schrenk, and W. Yant, Report of Investigation, U. S. Bur. of Mines, No. 8 (1936).
[5] A. Lusczak, Abhandl. Gesamtgebiet Hyg. **21**, 58 (1936).
[6] V. Henri, J. Phys. Rad. **3**, 181 (1922).
[7] H. Sponer, G. Nordheim, A. L. Sklar, and E. Teller, J. Chem. Phys., **7**, 207 (1939); W. Radle and C. Beck, J. Chem. Phys. **8**, 507 (1940).
[8] K. Wolf and W. Herold, Zeits. f. physik. Chemie **B13**, 201 (1931). K. Masaki, Bull. Chem. Soc. Japan **11**, 346 (1936).

Materials and methods

In order to establish a "working curve" specially purified toluene was obtained from the Barrett Company and this was loaded with various known amounts of benzene. From the law of partial pressures and vaporization constants, the concentration of benzene in the vapor could be computed. A hydrogen discharge tube carrying 0.75 ampere at 2000 volts was used as a source of radiation. The fused quartz absorption cell was 25 mm diameter and 120 cm long. It was provided with fused-on windows and graded seal inlet and outlet tubes. Due to the small diameter of the absorption tube, some of the radiation suffered several reflections from its walls before entering the spectrograph. A Hilger medium-sized quartz spectrograph served for the analysis of the radiation. Auxiliary lenses and diaphragms were employed to achieve uniform irradiation of the spectrograph slit and field and also to effect plate calibration with a step-sectored disk.

A 1.0-cc sample was introduced into the absorption apparatus by shattering a sealed-off glass vial after pumping the apparatus down to below 10^{-2} mm of mercury while at a temperature of 200°C. The liquid was then collected at one point of the apparatus by means of a cooling trap and allowed to come to equilibrium with its vapor at 23°C. The absorption cell was then pumped down to the desired pressure (usually 3.5 mm) and sealed off with a mercury manometer. Exposures were quite long due to the fact that measurements were carried out in a region strongly absorbed by toluene, i.e., 2500A. Repeated exposures of the same sample gave reproducible results. Measurement of the plates was carried out on a modified Bausch and Lomb densitometer.

The results are shown in Fig. 1 in which the logarithm of the concentration of benzene in the vapor mixture is plotted against the logarithm of the ratio of the background exposure to the benzene exposure. This curve is for the benzene band appearing at 2471A and the background adjacent thereto. Similar results were obtained for bands at 2528A and 2415A.

Discussion

An apparent departure from Beer's law was observed in this work and is to be explained partially by scattering in the collimating system and absorption cell or, to a lesser extent, molecular scattering. Deviations from the working curve are believed to be chiefly due to inaccurate pressure measurement and errors in densitometry. These are to be the subject of further investigation.

Use of the Rayleigh-Jeans Interference Refractometer

The Rayleigh-Jeans interference refractometer measures change in index of refraction by the

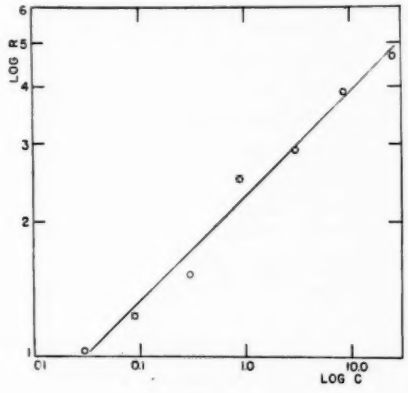

Fig. 1.

shift of an interference pattern. Its use is based on the assumption, which proves correct to a close approximation, that the refractivity of a mixture of gases is equal to the sum of the refractivities of the constituents times the percent of each present in the mixture.

The instrument is useful for measuring one variant in a mixture of gases, if the other component gases remain constant in proportion. Where more than one component gas varies, the results cannot be interpreted quantitatively.

The calibration relating change in refractivity to the shift of the interference pattern was made by the method of J. D. Edwards.[9] When the change in refractivity is determined with proper experimental precautions the concentration of the vapor in question may be calculated. So far as we know, the value for the index of refraction of toluene vapor is not available. The value used for vapor was computed from the value published

[9] J. Edwards, J. Am. Chem. Soc. **39**, 2382 (1917).

for liquid toluene by the Lorenz-Lorentz formula.

$$\frac{N^2-1}{N^2+2}\cdot\frac{1}{d}=K.$$

The interference refractometer was used to measure the concentration of toluene vapor in exposure chambers suitable for toxicological studies. Several types and sizes of chambers have been employed. The installation and methods of measurement with one of these chambers will be described.

The exposure chamber was of 1032 cu. ft. capacity. The air was circulated rapidly by means of a fan in a set of recirculation ducts, and 130 cu. ft. per minute of fresh air was supplied to the chamber. This arrangement was sufficient to eliminate the building up of CO_2 and water vapor in the chamber and to prevent the upset of the basic O_2-N_2 relation, even when three subjects were in the chamber.

At the beginning of an exposure, sufficient toluene was vaporized in the chamber to bring the concentration to the desired level; toluene vapor was then introduced into the air inlet duct to bring the air supplied up to the concentration in the chamber. At low concentrations (up to 200 p.p.m.) a bubbler was used; at high concentrations (between 200 and 800 p.p.m.) a drip arrangement brought the supplied air up to the desired concentration of toluene vapor.

A copper tube sampling duct was run into the exposure chamber, the end being so placed as not to be influenced unduly either by the subjects, or by the inlet or outlet openings. Sampling ducts were provided with tubes containing $CaCl_2$ to remove water vapor and ascarite to remove CO_2. Samples were drawn slowly into the instrument by connecting to a vacuum line. Pressure equilibrium was reached quickly after the vacuum was shut off.

The balance point or coincidence reading for the two interference patterns had been established with dry, CO_2-free air. Samples of air containing toluene were drawn into one of the chambers of the instrument, the interference pattern shift read, and the amount of toluene in the air determined.

Frequent determinations with the instrument permitted control of concentration within the chamber by proper adjustment of the bubbler or drip apparatus.

Discussion

Concentrations of toluene determined from its physical and molecular constants were set up in the exposure chamber and readings checked against those predicted from the calibration of the instrument. In addition, this eliminated the possibility of absorption of appreciable amounts of the toluene vapor by the drying tubes, condensation on the sampling duct or exposure chamber walls.

On certain days "controls" were run, when the subjects were in the chamber with no toluene vapor. Readings made with the interference refractometer on these days stayed steadily at the coincidence point for air. This showed that the drying tubes were adequate and that supply of fresh air was sufficient to prevent any upset of the O_2-N_2 proportions in the chamber during a long (8-hour) exposure.

A Recording Spectrophotometer and Spectropolarimeter*

WALLACE R. BRODE AND CHARLES H. JONES
Ohio State University, Columbus, Ohio

INTRODUCTION

THE color chemist, when first introduced to the art of spectrophotometry, found available for his use what has come to be known as the standard visual spectrophotometer. He was, no doubt, unhappily impressed with the immense amount of time required to make a single spectrophotometric determination with instruments of the visual type. This type of instrument requires that the transmission of the test sample be determined with high precision under illumination by homogeneous light at about thirty different wave-length settings within the visual region of the spectrum. Since at least five settings are usually necessary at a single wave-length, the possibility that an instrument could be devised to determine these data and record them automatically became a subject of investigation.

The first sensibly significant contribution in the way of an automatic recording spectrophotometer was made by K. S. Gibson[1] who built a spectrophotometer in which the human eye was replaced by a photoelectric cell. Although this instrument was not appreciably more rapid than the visual type, it did demonstrate that the sensitivity of the photoelectric cell was of the required order of magnitude. Next in line among the workers in this field of investigation was Arthur C. Hardy[2,3] whose interest in a rapid means of spectrophotometry arose in connection with his work in the field of color printing. He set about investigating the possibility of the use of the photo-cell with an associated vacuum tube amplifier as a means of measuring radiant energy only to find that the electrical response of such a combination upon exposure to light varied in a manner that defied calibration. Faced with this situation. Hardy set out to develop a "null" method of photoelectric spectrophotometry. He assumed it to be axiomatic that, if two beams of light of the same spectral quality and state of polarization impinge alternately from the same direction upon the same area of a light sensitive cell, the two beams may be adjudged equal when the fluctuations in the response of the cell due to the alternation of the light are at a minimum, and that if an absorbing substance be placed in one beam and the intensity of the other beam be adjusted until the fluctuations of the cell are at minimum, then it may be assumed that a condition of photometric balance has been attained. The photoelectric signal obtained in the above manner was coupled to a mechanical recording device that tended to seek the point of balance as the wave-length of light was changed, and this recorded on a graph paper by a mechanically driven stylus.

With the preceding fund of information and experimentation in mind, a phototype spectrophotometer, patterned somewhat after one built by Professor A. C. Hardy at the Massachusetts Institute of Technology, was constructed at the Ohio State University in 1934–1936. Without here discussing the design details of this prototype spectrophotometer, suffice it to say that its performance was excellent. By 1937, however, the science of automatic photometric instrumentation had progressed to such an extent as to

FIG. 1. Recording spectrophotometer and spectropolarimeter.

* Presented at the Ninth Summer Conference on Spectroscopy and Its Applications at Massachusetts Institute of Technology, Cambridge, Massachusetts, July 21–23, 1941.

[1] K. S. Gibson and others, Nat. Bur. Stand. Sci. Paper No. 349 (1919).

[2] A. C. Hardy, J. Opt. Soc. Am. **18**, 99 (1929); **25**, 305 (1935).

[3] J. L. Michaelson and H. A. Liebhafsky, Gen. Elec. Rev. 445 (1936).

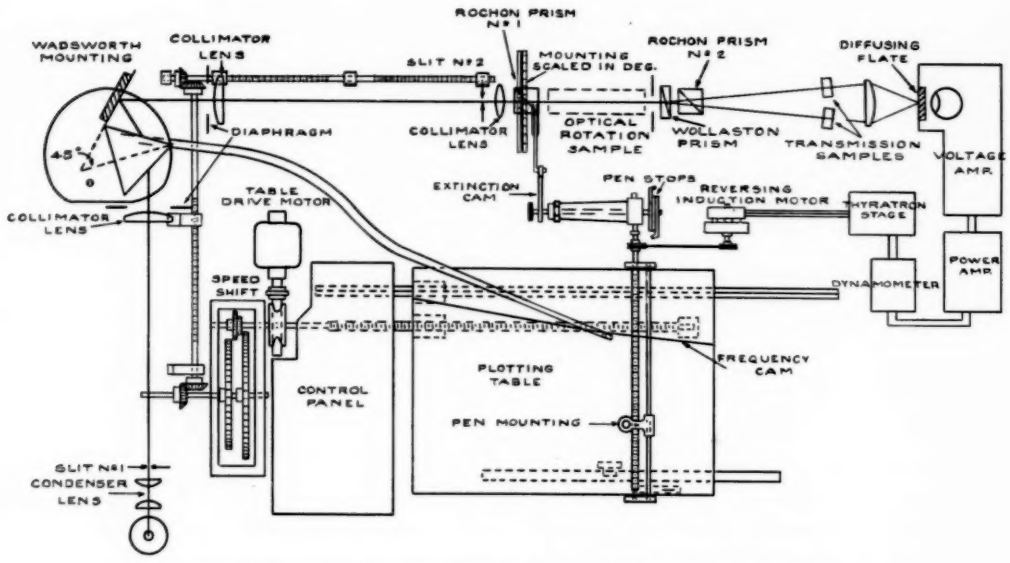

FIG. 2. Diagram of recording spectrophotometer and spectropolarimeter.

make desirable many changes in the instrument. In addition, we were interested in the possibility of developing the instrument as a recording polarimeter. Hence it was decided to redesign the photometer and electrical recording apparatus. In the prototype instrument a "flicker" photometer was used. This was found to be unsatisfactory in that at a point at which photometric balance would be expected, the photoelectric signals from the edges of the light chopper were greater than those due to the photometric quantities being measured. This caused difficulty in determining the balance condition. Also the plotting pen was driven by a small series motor powered directly from the amplifier, and, in regions of high absorption, insufficient power was supplied to this motor by the amplifier to give satisfactory measurement. The experience of Hardy had by this time demonstrated that a standard polarization photometer could be used in automatic recording instruments and it was decided to discard the flicker photometer and use a polarization photometer instead. The series-type pen motor was replaced by a dynamometer operated thryatron stage which was to drive a shaded-pole induction motor to move the pen.

The recording spectrophotometer and spectropolarimeter (Fig. 1) was designed and constructed to meet the needs of the color chemist and the research worker engaged in investigating the relation between optical properties and chemical structure of chemical compounds. The instrument plots the light frequency dependence of two important qualities: the extinction coefficient and the optical rotation.

DESCRIPTION OF DESIGN OF THE INSTRUMENT

The design of the instrument is shown schematically in Fig. 2. The table upon which the assemblage is mounted is of solid construction with a white pine top.

The source of illumination is a General Electric projection lamp of the following specifications: 100 watt, 115 volt, T-8½, filament cc-13. The lamp is operated on d.c.

The monochromator is a modified Wadsworth[4] type as shown in Fig. 2. The optical bench of the monochromator is carefully machined and rigidly fastened to the instrument table. The monochromator lenses are made from crystalline quartz cut so that the optical axis of the quartz coincides with the axial direction of light in the monochromator. The lens mountings are movable

[4] Wadsworth, Phil. Mag. **38**, 337 (1894); **1**, 232 (1895).

upon the optical bench. Light from the lamp is focused upon slit No. 1 by a condenser lens combination. The light issuing from slit No. 1 is collimated and, after passing through a 60° prism, is reflected by a front-face aluminized mirror into a second collimator which focuses the dispersed light at slit No. 2. The dispersing prism is mounted upon a revolvable table and is set at its angle of minimum deviation so that a plane through its center and parallel to its base coincides with the optical axis of the system. The prism table is constructed so as to use interchangeable 60° prisms and the instrument is provided with both glass and quartz prisms. The quartz prism is cut with the principal axis parallel to its base so as to avoid double images at the angle of minimum deviation. The prism is oriented so that a plane bisecting the solid angle opposite the non-refracting surface passes through the axis of rotation of the prism table. The reflecting mirror is located upon the prism table so that a plane passing along the reflecting surface intersects the axis of rotation of the prism table and makes an angle of 45° with the above-mentioned plane through the prism and the axis of rotation of the table. In this type of mounting of prism and mirror, the assumption is that the frequencies of dispersed light falling upon the exit slit have been bent 90° in traversing the system from the source and that all other frequencies have been bent by some other angle and hence do not fall upon the exit slit.

The photometer plan is outlined and the imaging illustrated in Fig. 3. Inspection of the plan will show that it is a modification of the standard polarization photometer. In fact, excepting the flicker prism 7, the optical parts were taken from a Jobin and Yvon photometer. The photometer is essentially the same as that used in the commercial Hardy recording spectrophotometer. Light enters the photometer from the monochromator exit slit *1* and is polarized by Rochon prism *3* which deviates the light of unwanted polarization *4*. The wanted and unwanted polarizations are separated by stop *5* because the angle which the dispersing prism subtends at the photometer collimator lens *2* is smaller than the angle of deviation. The wanted beam, after being doubled by the Wollaston prism *6*, is again doubled by the flicker prism *7*, but only the deviated beams are passed by stop *11*, where they form slit images *16* and *17*. A flicker variation in the photometer is caused by Rochon prism *7* which is mounted in a hollow shaft of a synchronous induction motor. The two beams of wanted polarization are focused upon a diffusing plate *13* by photometer lens *12*. The diffused light falls upon the photo-cathode *14* of a photoelectric cell.

Basic Formulation of Operation of the Instrument

A. As a photometer*

Let the azimuth of the Rochon prism *3* with respect to one of the planes of the Wollaston prism *6* be a. Then the amplitudes of the two beams as they emerge from the Wollaston prism are, respectively, $A_1=A\sin a\sin wt$ and $A_2=A\cos a\cos wt$, where $w=2f$. The corresponding intensities are $I_1=A^2\sin^2 a\sin^2 wt$ and $I_2=A^2\times\cos^2 a\cos^2 wt$. If now the beam of intensity I_1 is transmitted by a sample having a transmittancy factor T_1 and beam of intensity I_2 is transmitted by a sample having a transmittancy factor T_2, the instantaneous value of the light received by the photo-cell collector is proportional to I_1T_1 plus I_2T_2, thus

$$I=I_1T_1+I_2T_2$$
$$=A^2(T_1\sin^2 a\sin^2 wt+T_2\cos^2 a\cos^2 wt).$$

Assuming that $A^2=2$, as a matter of convenience and making a few simple algebraic transformations,

$$I=(T_1\sin^2 a+T_2\cos^2 a)-(T_1\sin^2 a-T_2\cos^2 a)\cos 2wt.$$

Since the photo-cell current is a linear function

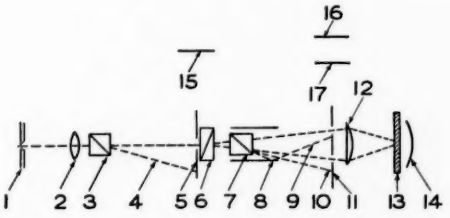

FIG. 3. Optical arrangement of photometer-polarimeter.

*A similar analysis has been applied to the Hardy recording spectrophotometer, J. Opt. Soc. Am. **25**, 305 (1935).

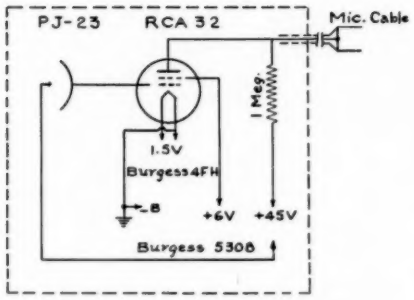

FIG. 4. Photo-cell preamplifier.

of the light intensity over the range considered, this equation when multiplied by a suitable proportionality constant represents the instantaneous value of the cell current. It will be seen that the cell current consists of a steady component proportional to $T_1 \sin^2 a + T_2 \cos^2 a$ and an alternating component of the frequency $2f$ and amplitude proportional to $R_1 \sin^2 a - R_2 \cos^2 a$. Since *9* rotates at 1620 r.p.m. the frequency of the alternating component is 54 cycles per second. The a.c. from the photo-cell collector is amplified by means of an a.c. amplifier tuned to this frequency and is transmitted to an a.c. motor. The direction of motion of the a.c. motor depends upon the phase of the a.c. signal entering it and this is determined by which of two thyratrons is tripped, which is in turn determined by the motion of the moving coil of a dynamometer whose direction of motion is decided by the phase of the current leaving the amplifier, which depends upon whether $T_1 \sin^2 a$ is greater or less than $T_2 \cos^2 a$. By means of a cam and a pair of worm gears, the motor is made to rotate prism *4* toward the position for which $T_1 \sin^2 a - T_2 \cos^2 a = 0$. At this point the photoelectric current is zero, and the torque tending to turn the motor is zero and the motor stops and a position of photometric balance is assumed to have been realized. If T_1 is the known transmittancy of a standard specimen, the transmittancy factor T_2 of an unknown sample may be given directly in terms of a, since the above equation may be written

$$T_1/T_2 = \tan^2 a,$$

providing R_1 and R_2 are equal, where R is the reflection factor.

In the above analysis the transmittancy factor was used on account of its expository value. This instrument does not plot transmittancy factor T, but rather the extinction coefficient E. By fundamental definition the extinction coefficient E may be represented as follows:

$$E = kcd,$$

where k is the specific extinction, c the concentration of the absorbing substance and d the length of the absorbing path. Also,

$$E = kcd = -\log_{10} I_{T_1}/I_{T_2}$$

and, according to the above analysis,

$$I_{T_1}/I_{T_2} = \tan^2 a$$

where I_{T_1} is the light intensity transmitted by sample 1 and I_{T_2} is the intensity transmitted by sample 2. (I_{T_2} is made equal to unity by omitting sample 2 and making $R_1 = R_2$.) Then,

$$I_{T_1} = \tan^2 a$$

and

$$E = kcd = -\log_{10} \tan^2 a.$$

Thus it is possible with the aid of a cam of suitable characteristics to plot the extinction coefficient, E, due to a sample as the ordinate on the graph.

B. As a polarimeter

As explained before, photometric balance is indicated when $I_1 = I_2$ as the beams 1 and 2 reach the photo-cathode with no samples inserted in the beam, then

$$I_1/I_2 = \tan^2 a;$$

but, since $I_1 = I_2$, $\tan^2 \alpha = 1$ and $\tan a = 1$ whence $a = 45°$ which is the angular position of the polarizing plane of 4 with respect to the two polarizing planes of the Wollaston prism *6*. Since this position has no other physical significance than that it is the position for which $I_1 = I_2 = k$, and since 45 mechanical degrees of rotation must be made by *4* to make $I_1 = 0$ and $I_2 = 2k$ or vice versa, then we may denote the position $a = 45°$ with respect to one of the planes of *6* as our zero point. If this be taken as the zero position and the instrument be considered as a polarimeter, it may be seen that placing a substance which rotates the plane of polarization of

the plane polarized light between prisms *4* and *8* will cause a photometric unbalance in that I_1 will then be different from I_2 since the zero condition was initially achieved by setting the plane of *3* 45° with respect to the planes of *6*. This zero condition can be re-established by rotating *3* in a direction opposite to the direction of rotation of the optically active substance placed between *3* and *6*; this is the equivalent of having achieved a polarimetric balance, and the mechanical displacement of *3* from its zero position may be read as the rotation of the optically active sample in degrees. It will be immediately seen upon recalling the performance as a photometer that the conditions for polarimetric and photometric balance are identical, and any condition of unbalance in either case is compensated by a rotation of *3*. Hence, if a cam of proper characteristics be supplied to locate the position of *3* by means of the pen motor, the position of polarimetric balance can be indicated by a pen position (point on a graph) just as in the case of the photometric curve. Thus a plot of the frequency dependence of the optical activity of a sample may be achieved with exactly the same recording mechanism as was used for photometric recording.

The Ordinate Plotting Mechanism

The a.c. output from the photo-cell is amplified first by a photo-cell preamplifier, a circuit diagram of which is shown in Fig. 4, then by a voltage amplifier and finally by a power amplifier. The power amplifier operated the moving coil of an a.c. dynamometer, the stationary coil of which is powered independently with a current of the same phase as that powering the flicker motor. The moving coil operates two contacts which control two thyratrons which determine the direction of rotation of the pen-drive motor. A circuit diagram showing the amplifiers, dynamometer and motor is indicated in Fig. 5. The direction of motion of the plotting pen-drive motor is determined by the phase of the a.c. delivered to the dynamometer moving coil by the amplifier, which in turn depends upon which of the two photometer beams is the more intense. This depends upon whether the extinction due to the sample increases or decreases as the frequency of the light is changed. The motion of the extinction cam and, hence, the pen is always in the direction tending to match the two photometer beams and thus achieve photometric balance. Thus the instrument, as a spectrophotometer, is capable, when equipped with a suitable cam, of plotting the extinction coefficient as a continuous function of the frequency of light. The range of plotting with the glass prism is from 300 fresnel units (10,000A) to 789.5 fresnel units (3,800A). Observations analogous to the above may be made regarding the rotatory dispersion-frequency plot. Measurements made with the quartz prism and a G.E. quartz enveloped photo-cell using a hydrogen arc as a light source[4] indicate a working sensitivity to 1200 fresnel (2500A) in the ultraviolet.

The Design and Cutting of Ordinate Plotting Cams

Since the Rochon prism is rotated by means of a lever arm operated by a cam, and since its moment arm changes as the prism is rotated, it would be foolhardy to try to calculate a cam to record any physical function of the photometer. However, the mechanical mounting of the prism

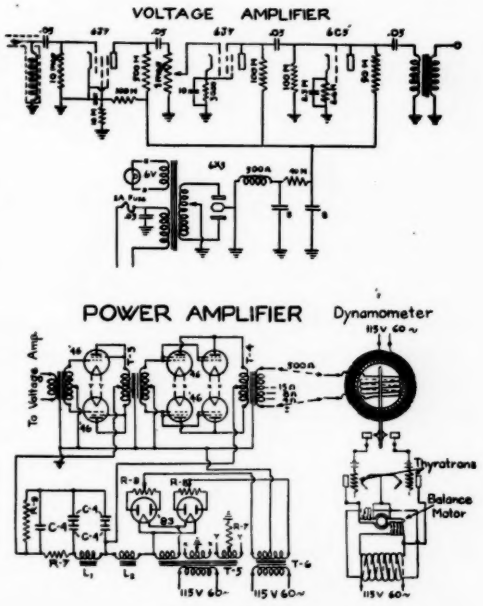

FIG. 5. Amplifier diagram.

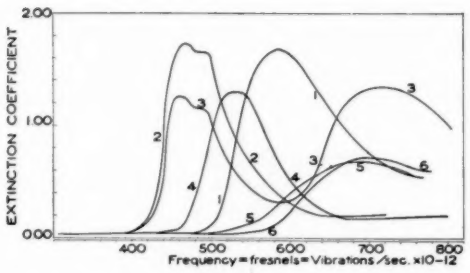

FIG. 6. Tracing of recorded data on absorption spectra of Cellophane filters (see reference 5 in text, Fig. 12.30, p. 269).

is provided with a scale and vernier by which the angular setting of the prism may be read in degrees with an accuracy of at least 0.1 of a degree. Furthermore, data are available giving the extinction value in a polarization photometer as a function of the extinction angle which can be satisfactorily applied to this photometer.[5] As a first approximation to the desired cam, a cam was cut which gave the correct extinction angles for the corresponding E values indicated by positions of the pen on the plotting paper. As a second and final approximation, the cam was adjusted to read the correct extinction values for the $f=512.8$ band of a neodymium glass available in this laboratory, the data on which are accurately known. It should be noted at this point that the energy transmitted by the amplifier was kept at a constant value for all points determined.

In a manner exactly analogous to that described for determining a first approximation to an extinction cam, a cam to record optical rotation was cut to indicate the correct angular settings of the extinction prism for corresponding positions of the pen on the plotting paper designed to plot optical rotation against frequency of light. Such a cam would plot either positive or negative rotation depending upon the phase of the a.c. current being supplied to the dynamometer moving coil. This can be predetermined by switching the flickermotor on and off until the appropriate time-phase is obtained. In this case it was decided to apply corrections to the standard graph paper rather than to adjust the cam. For this purpose a standard quartz plate 1 mm thick whose angular rotations were known at a number of wave-lengths was used.

FREQUENCY CALIBRATION

The frequency of light falling upon the exit slit of the monochromator is determined by a cam located upon the plotting table and whose motion is transmitted through a lever arm to the carriage upon which the dispersion prism is mounted. The length of this level arm from the point at which it touches the frequency cam to the center of rotation of the prism table is 107 cm. This characteristic was introduced to facilitate cutting an accurate frequency cam without too great difficulty. The curvature of the cam was found by plotting positions of the lever arm against lines of the mercury arc for 18 different mercury lines. A smooth curve was drawn through these points and a cam of the same curvature was cut and located upon the table. The cam was then checked against positions on the graph paper for plotting extinction against frequency and the cam scraped to adjust to the correct values. This cam was rigorously calibrated only from 388.0 f to 800.0 f, but, since the dispersion of the prism is so small in the red end of the spectrum, an extrapolation of the curve for the visible was made to extend to 300 f. This extrapolation is, in all probability, accurate to a few fresnel units, although no way of checking this has occurred to the writer inasmuch as near infra-red frequency measurements on most filters are probably more in error than is the frequency cam on this instrument.

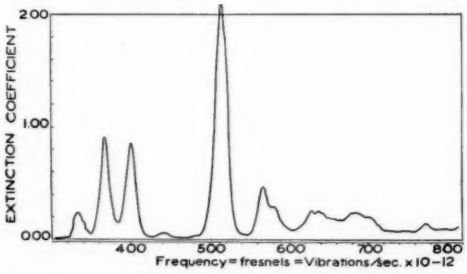

FIG. 7. Tracing of recorded data on absorption spectrum of a neodymium glass.

[5] W. R. Brode, *Chemical Spectroscopy* (John Wiley and Sons, New York, 1939).

Precision

Frequency values in fresnel units can be determined with a precision within 2 fresnel units for the entire range measured. A single extinction coefficient value may be determined with a reproducibility within the width of the point plotted by the pen for E values below 1.80 For E values from 1.80 to 2.00 as high as 5 percent error in determining a single E value is considered as being present.

In polarimetric measurements the precision is the same as that for E values below $E=1.80$ when the extinction of the sample is less than $E=1.80$.

Application Photomultipliers to Photoelectric Photometry

Experiments have been conducted on the application of secondary emission photomultipliers as light sensitive units in alternating-current photometry. The conclusion from our experimentation is that the signal-to-noise ratio in photomultipliers available at present is unfavorable to this type of application and that a superior signal-to-noise ratio can be obtained by using a photoelectric cell plus a vacuum tube amplifier.

Applications of the Instrument

Existing visual spectrophotometers do nothing that this automatic recording spectrophotometer does not do. For practical and research applications of such instruments reference should be made to Wallace R. Brode's book, *Chemical Spectroscopy*, sections on visual spectrophotometry.[5]

This instrument is, however, at least ten times as fast in operation as the standard visual spectrophotometer. It is completely automatic thus removing personal observational error in determining data. It has a wider spectral range than the existing visual instruments, being capable of operation from 300 fresnel units to 800 fresnel units. The near infra-red recording capacity enables it to be used for determination of characteristics of substances to be used as heat filters. Its recording precision extends to the limit of the violet where it is very difficult to obtain measurements visually. Fig. 6 shows measurements on five samples of colored Cellophane. Fig. 7 shows measurements on a neodymium glass.

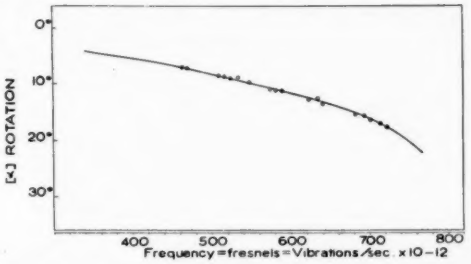

Fig. 8. Tracing of recorded data on rotatory dispersion of sucrose (circled points are published observations of Lowry and Richards, reference 6).

This instrument is, moreover, the only instrument existing to the author's knowledge which records continuously the rotation due to optical activity in a compound as a function of frequency of light. Figure 8 shows a plot of the rotatory dispersion of sucrose (conc. 8.66 g/liter). For purposes of comparison the values as published by Lowry and Richards[6] are indicated by encircled dots.

The instrument will probably find its greatest usefulness in the study of the relation between absorption and rotation. The rotatory dispersion curves of sugars and amino acids in their pure form and in combinations to form the corresponding simple saccharides and proteins should yield valuable data for the prediction of the structure of more complicated compounds in these series.

[6] T. M. Lowry and E. M. Richards, J. Chem. Soc. **125**, 2511 (1924).

Proceedings of the Twenty-Sixth Annual Meeting of the Optical Society of America

HOTEL PENNSYLVANIA, NEW YORK CITY, OCTOBER 24–25, 1941

THIS meeting was originally planned as a joint celebration of the Tenth Anniversary of the founding of the American Institute of Physics. Although these plans were canceled because of the Defense Emergency, three of the Founder Societies decided to meet concurrently at the time and place for which arrangements had already been made. The wisdom of this course was demonstrated by the acknowledged success of the undertaking.

SYMPOSIUM OF INVITED PAPERS ON OPTICS IN THE NATIONAL DEFENSE

The meeting was opened by President Gibson on Friday, October 24 at 10 A.M. with a symposium of invited papers on "Optics in the National Defense." Although many details were necessarily omitted because of the nature of the subject matter, a vivid picture was portrayed of the role of optical science in the defense of our nation.

Lieutenant S. S. Ballard introduced a discussion of optical problems facing the Navy by stating that the greatest optical problem before the Navy at the present time is procurement; the bottleneck is not raw materials, but shortages of machinery and men. Because of this, short-cuts in manufacturing methods must be developed; and the use of modified optical equipment, constructed by simpler processes, must be introduced. Examples of the latter are plastic lenses which require no grinding and polishing, and the use of laminated glass gelatin filters instead of colored glass filters.

The Navy employs optical equipment for two major purposes—navigation and fire control. Navigation is based on one of the simplest of all optical instruments, the sextant. A more complex optical instrument is the submarine periscope, which performs the duties of searching, navigation, and fire control, while withstanding the severe environmental conditions under which it must be used. The problem of fire control covers not only various types of range finders for ship and anti-aircraft guns, but also torpedo and bomb sights. The present war has brought anti-aircraft fire control, relatively unimportant in the last war, into great prominence. New problems are involved, it was stated, because the greater velocity of the target allows less time to man, train, and fire the guns.

In the design and use of range finders, Lieutenant Ballard cited the conditions of vibration and ship motion, shock from gunfire, and exposure to the elements, as problems which must be met by an optical instrument fifteen feet long of such sensitivity that it will measure an angle as small as half a second of an arc.

Although the details are closely guarded secrets, the speaker assured the audience that the Navy is carrying on research at a greatly accelerated rate. This work is employing the full time of more than a score of the nation's leading scientists. The organization handling new developments was briefly sketched.

Dead reckoning is the basis for all navigation; aerial navigation, because of the high speed and preoccupation of the personnel, necessitates new methods and equipment. Lieutenant J. T. Hayward described in some detail the problem of measurement of drift, which is a function of force, direction, and variability of the wind, and the velocity of the plane. In order to dramatize the use of drift measuring devices, the sextant, the chronometer, and other instruments used in aerial navigation, the speaker took the audience on an imaginary trip from San Francisco to Hawaii as seen through the eyes of the navigator of a Consolidated Catalina "boat." The successive steps of consulting charts, estimating weather conditions, and calculating velocities were vividly described. After encounters with head winds, bad weather, and momentary loss of position at sea, the journey was successfully completed.

Lieutenant Hayward also touched upon the even more difficult problems of carrier aircraft, which must control accuracy of navigation in order to find their ship, moving at perhaps 30

knots, from a distance of four hundred miles or more.

Dr. Kingslake sketched the early history of aerial photography from the first aerial pictures taken on wet plates from a captive balloon over Paris in 1856, through the first photographs from an aeroplane in flight by Wilbur Wright in 1909, to the present day. Just prior to the outbreak of the war in 1914, attempts were made by the French and English to take photographs of military significance from the air. By the end of the war four years later, approximately one million prints were being made and distributed each month. Slides were shown of the very large cameras developed during the last war, some of them taking a seven by nine inch picture, using a lens with forty-eight inch focal length. The use of magazines for glass plates further increased the bulk of these cameras.

Later developments have recognized three different types of aerial photography, each having special equipment requirements. These are (1) reconnaissance photography, (2) night photography, and (3) mapping photography. In reconnaissance photography, great detail is required. This is achieved by the use of large cameras and contact prints, lenses of long focal length and necessarily small field, and the use of infra-red materials. The altitudes now used for aerial photography are great, not uncommonly 40,000 feet. Night photography not only calls for constant improvements by supplying brighter flashes, faster lenses, and faster film, but also for newer methods for synchronization of the shutter of one or more cameras with the flash. An example of faster lenses developed for night photography is the f:3.5 lens with focal length of fourteen inches. In aerial survey work, a lens is required to cover a very wide field without distortion. The covering power obtainable is illustrated by the fact that a nine-by-nine inch plate is covered without distortion by a lens of six-inch focal length.

The preparation and use of optical crystals for military and industrial purposes was discussed by Mr. Frederick Bates, Chief of the Optics Division of the National Bureau of Standards. The speaker assigned a large part of the success of the blitzkrieg technique to the use of quartz crystals as high frequency oscillators in the two-way communication systems between the parts of a mechanized army. The modern military force bereft of its optical instruments was compared by the speaker to a man without sight or hearing.

The search for satisfactory crystals from which to cut electric oscillators was discussed with the aid of numerous slides illustrating the appearance of various grades of quartz crystals by polarized light. The detection of optical twinning, occlusions, and other irregularities was described as well as the phenomenon of electrical twinning, involving some unknown shift in atomic position.

In concluding his discussion, Mr. Bates exhibited slides of fine crystals of Iceland spar from deposits in New Mexico. Several other illustrations of interesting crystals, a few of the innumerable samples sent to the National Bureau of Standards for evaluation from all parts of the North American continent, were shown.

Dr. Walter G. Driscoll described the general organization and work of the Technical Laboratories of the Federal Bureau of Investigation, now doing important work in the maintenance of our national security through the forensic application of chemistry, physics, toxicology and serology. In this work, optical instruments are used more frequently than any other type of equipment. Petrographic microscopes are used for the examination of soils, minerals, dirt, and debris. Metallurgy is often vital in the investigation of sabotage, as in the examination of destructive metals in lubricants, the tracing of tools to individuals by detection of adhering metal, and similar applications. Microscopic equipment is indispensable for microspectrophotometry, microchemical analysis, and firearms identification. In the cryptographic section, various optical tools, such as the microscope, the opacimeter, and illumination by ultraviolet light are constantly used.

Although specific cases could not be discussed because of the nature of the work, the speaker stated that optical equipment was coming into more general use in the detection of crime, and that skepticism of scientific methods, once prevalent among many police officers, no longer exists.

Joint Luncheon

At the Joint Luncheon of the Acoustical Society of America, the Society of Rheology, and the

Optical Society of America, the guest speaker, Dr. Vannevar Bush, described the organization of scientific research in this country in the interest of National Defense. The National Defense Research Committee was formed as part of the Office of Emergency Management by executive decree in June, 1940. As an executive body it was instructed by the President to supplement the work of the Army and Navy in developing the instrumentalities of war. There was no need for the formation of an advisory group, because of the existence in that capacity of the National Academy of Sciences and the National Research Council. The National Defense Research Committee, through its four divisions and sixty sections, operates primarily by means of contracts with universities, colleges, research institutes, and industrial organizations; about four hundred such contracts are now active.

In July, 1941 the Office of Scientific Research and Development was established to coordinate all defense research activities. The O.S.R.D. consists of the National Defense Research Committe, a business office, a liaison office (handling the very important interchange of information with Britain) and a newly-formed Medical Research Commission.

Dr. Bush emphasized that the scientists of this country have done more than talk about the subject of national defense. They have taken off their coats and gone to work; they are united in their efforts, and are "going places."

Annual Dinner and Award of the Frederic Ives Medal

On Friday evening a joint dinner was held for members of the Optical Society of America, the Society of Rheology, and their guests. Dr. Gibson, who described himself as "the about-to-expire president of the Optical Society," introduced the officers of the Society of Rheology to the audience. Dr. E. O. Kraemer was then called upon, in the regrettable absence of Professor E. C. Bingham, to deliver an address on the "Commemoration of the Centenary of the work of Poiseuille." Despite Dr. Kraemer's avowed unpreparedness, he presented a succinct and critical outline of the career of the father of modern experimental rheology. Poiseuille's training in medicine and his interest in the circulation of the blood led to his classical studies of the flow of fluids in capillaries; this work may still be admired, not only because of the conclusions reached, but for the high precision and care exercised in spite of the limited facilities of his time.

Dr. Gibson then introduced the newly-elected officers of the Optical Society. Following this, the Chairman of the Committee on Award of the Frederic Ives Medal, Dr. Rudolf Kingslake, was called on to read the citation. President Gibson then formally bestowed the medal on Dr. Selig Hecht. The citation and the Medalist's address on "The Quantum Relations of Vision" will be published in a later issue of this Journal.

Business Session

A brief business session was held on Saturday morning, October 25, at 9:45 A.M., President Gibson presiding. Formal reports of the Secretary, Treasurer, and Editor of Publications for the calendar year 1940* were accepted and placed on file. Informal reports covering the period from January 1, 1941 to the time of the annual meeting in 1941 were also presented.

Contributed Papers

Sessions for the reading and discussion of contributed papers continued throughout Friday afternoon and Saturday, the authors' abstracts of these papers being appended.

Registration

There were 202 persons registered at this meeting of the Optical Society, and doubtless many others present who did not register. The attendance at the joint luncheon of the three Founder Societies was very impressive, filling the Grand Ball Room of the Hotel Pennsylvania.

Meeting of the Board of Directors

A meeting of the Board of Directors was held on Thursday, October 23, 1941. Minutes of the meeting are appended.

Arthur C. Hardy, *Secretary*

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* Published in J. Opt. Soc. Am. **31**, 449–455 (1941).

Minutes of the Eighteenth Meeting of the Board of Directors of the Optical Society of America, Incorporated

HOTEL PENNSYLVANIA, NEW YORK CITY, OCTOBER 23, 1941

IN addition to the transaction of routine business and the receiving of reports from chairmen of committees and representatives, the following items of general interest to members of the Society were considered.

Announcements by Secretary

Results of Letter Ballots:

1. Appointment of Selig Hecht as O. S. A. Representative on the Council of the A. A. A. S.
2. Appointment of the following members of the Glossary Committee:

E. Q. ADAMS	F. W. JOBE
FRANK BENFORD	D. B. JUDD
W. M. CADY	E. F. KINGSBURY
H. P. GAGE	W. W. LOZIER
I. C. GARDNER	G. W. MOFFITT
A. N. GOLDSMITH	RALPH A. SAWYER
G. G. HARVEY	L. E. VARDEN

3. Resolutions to hold O. S. A. meeting on October 24 and 25, 1941 at the Hotel Pennsylvania, New York City, and to hold the O. S. A. meeting in February, 1942 at the Johns Hopkins University in Baltimore, Maryland.
4. Resolutions to declare the present Secretary and Treasurer eligible for re-election in October, 1941.
5. Appointment of Tellers for 1941 election

G. G. HARVEY, *Chairman*	GEORGE WALD
D. C. STOCKBARGER	F. W. SEARS, *Alternate*

6. Amendment of O. S. A. By-Laws pertaining to Student Membership.

Report of Tellers

The report indicated the election of the following officers:

For a term of two years beginning October 25, 1941:

President: A. G. WORTHING
Vice President: A. H. PFUND

For a term of four years beginning October 25, 1941:

Secretary: A. C. HARDY
Treasurer: H. F. KURTZ

Members at large of the Board of Directors:

DEANE B. JUDD
DAVID L. MACADAM
RALPH A. SAWYER

Membership

The Secretary reported that between January 1 and October 22, 1941, five members had died, 149 new members have been elected as of January 1, 1941, and 23 as of January 1, 1942.

Transfer from Associate to Regular Membership

On recommendation of the Committee on Transfer, 102 associate members were approved for transfer to regular membership. The names of these transfers will be published in the annual report of the Secretary.

Treasurer's Report

The Treasurer gave an informal report of the financial status of the Society as of October 1, 1941, the details of which will be incorporated later in his annual report.

Amendments to By-Laws

The Board approved the following resolutions amending the By-Laws:

Resolved:—That Section 4 of Article III be amended by striking out the words "affirmative vote of three-fourths ($\frac{3}{4}$) of the entire Board" from the last sentence of the third paragraph, and substituting the words, "affirmative vote of a majority of the entire Board."

Resolved:—That Section 6 of Article III be amended by striking out the sentence reading: "Where more than two candidates are nominated for any one office, the voting shall be by preferential ballot."

Resolved:—That Section 7 of Article III be amended by striking out the words "may fill such vacancy until the next annual meeting of the corporation," and substituting the words, "may fill such vacancy for the unexpired term of office."

Resolved:—That Section 1 of Article V be amended by inserting in the last sentence the word "student" after the word "associate."

Announcement of Appointments

1. Representative on Sectional Committee of A. S. A. on Motion Pictures, Z-22:
B. H. CARROLL

2. Representatives on Sectional Committee of A. S. A. on Safety Glass, Z-26:
E. D. TILLYER
N. F. BARNES (*alternate*)

3. Representative on American National Committee for International Congresses on Photography:
A. C. HARDY

Nomination of A.I.P. Representative

K. S. Gibson was nominated to succeed W. B. Rayton as O.S.A. Representative on the Governing Board of the American Institute of Physics.

ARTHUR C. HARDY, *Secretary*

DECEMBER, 1941 J. O. S. A. VOLUME 31

Program of Sessions

(TITLES AND ABSTRACTS OF PAPERS)

Symposium of Invited Papers

OPTICS IN THE NATIONAL DEFENSE

1. **Optical Problems Facing the Navy.** LIEUT. S. S. BALLARD, *Bureau of Ordnance, Navy Department, Washington, D. C.*
2. **Optical Instruments in Aerial Navigation.** LIEUT. J. T. HAYWARD, *Naval Aircraft Factory, Navy Yard, Philadelphia, Pennsylvania.*
3. **Lenses for Aerial Photography.** RUDOLF KINGSLAKE, *Optical Designer, Eastman Kodak Company, Rochester, New York.*
4. **Optical Crystals for Industrial and War Purposes.** FREDERICK BATES, *Chief, Optics Division, National Bureau of Standards, Washington, D. C.*
5. **Optics in Sabotage and Espionage Investigations,** WALTER G. DRISCOLL, *Technical Laboratories, Federal Bureau of Investigation, Washington, D. C.*

Contributed Papers

6. Pressure of Radiation on a Moving Absorbing Surface. HERBERT E. IVES, *Bell Telephone Laboratories.*

The reflected energy density in front of a moving perfect reflector was derived by Larmor as

$$E_M = E_s\left(\frac{c+v}{c-v}\right)^2, \tag{1}$$

where E_s = energy density with the mirror stationary, E_M = energy density with the mirror moving, c = velocity of light, and v is the velocity of the mirror. From this Larmor, Abraham, and others find the pressure of radiation on the moving mirror to be

$$P = 2E_s\left(\frac{c+v}{c-v}\right). \tag{2}$$

On a moving totally absorbing surface, Poynting and Abraham derive the pressure

$$P = E_s(1+v/c). \tag{3}$$

This value, as noted by Abraham, calls for a first-order variation of pressure with motion in a system of co-moving source and absorber. By using the definition—pressure x time of action = change of momentum in conjunction with (1), the mass equivalent of energy is derived as

$$m = (E/c^2). \tag{4}$$

If this mass equivalent is then used in the equation giving the change of momentum of energy on absorption, one derives for a moving totally absorbing surface, in place of (3), the value

$$P = E\left(\frac{c+v}{c-v}\right). \tag{5}$$

This value, which is exactly half that for a perfect reflector, is invariant with motion of the system source-absorber.

7. Propagation of Radiation in a Scattering and Absorbing Medium. E. O. HULBURT, *Naval Research Laboratory, Washington, D. C.*

It is assumed that radiation of intensity i_0 is incident on the surfaces of a slab of a medium which both scatters and absorbs the radiation. The slab is infinite in the hori-

zontal directions and of thickness t in the vertical direction. Equations are derived for ξ, η, ξ_0 and η_0, where at a distance χ below the upper surface of the slab ξ and η are the intensities of the streams of radiation flowing downward and upward, respectively; ξ_0 and η_0 are the respective intensities of the streams of radiation emerging from the lower and upper surfaces of the slab. The equations contain i_0 and hyperbolic functions of t, χ, σ and β; where σ and β are the scattering and absorption coefficients of the medium, respectively. The derivation lacks generality in that special cases of the scattering distribution are treated; a general treatment appears intricate. Applications of the equations are made to the brightness of clouds and to the color and brightness of the surface of the sea.

8. The Role of Absorption in Turbid Media. S. Q. DUNTLEY, *Massachusetts Institute of Technology.*

In a previous paper* dealing with the general theory of turbid media, an experimental method for evaluating the absorption and scattering coefficients was discussed. The technique involves the use of an oil-filled photometer and a special turbid medium diagram. Using the experimental procedures already developed, a study has been made of a series of oil and water emulsions in which the number of absorbing molecules per unit volume was held constant. These molecules were contained in the oil. Both oil-particle and water-particle emulsions were used.

* Abstract, J. Opt. Soc. Am. **31**, 463 (1941).

9. Dispersion Formula for Optical Glass. M. HERZBERGER, *Kodak Research Laboratories.*

A glass is frequently characterized by its index for one wave-length, n_d, and its Abbe value, ν_d, but no formula is found in the literature with which the refractive indices for other wave-lengths actually can be calculated from this data with sufficient accuracy. The author gives a formula to fill this gap for all ordinary glasses, a formula which allows extrapolation into the infra-red. Whereas ordinary glasses are given by two data, glasses with deviating secondary spectrum, as extra dense flints, telescope flints, KzFS glasses, and Kodak glasses, need four data to be sufficiently characterized. The additional data can be chosen such that their values are zero for ordinary glasses and indicate to the optical designer the change in secondary spectrum.

The formula arrived at is a dispersion formula common to all glasses, suggesting that all ordinary glasses have the same two distinct absorption bands in the ultraviolet. The formula characterizes all commercial glasses with an accuracy which is $\leqq 2.10^{-5}$ throughout the visible spectrum.

10. Computation of Optical Errors of High Order in Systems of Spherical Surfaces. BENJAMIN L. SNAVELY, *Lehigh University.*

This paper describes a general method for computing to any desired degree of accuracy the errors in the image in any optical system of plane and spherical refracting or reflecting surfaces. The method is applicable to uncentered systems. It is particularly hoped that the final formulae will be found sufficiently concise to provide a satisfactory method for calculating the errors in a centered system associated with the skew rays. The problem is approached through Hamilton's *point characteristic.* The concept of rays is almost entirely avoided although, for a given object point, computations are most conveniently handled in a coordinate system which has its axis along a ray passing through the approximate center of the exit pupil. A wave originating at any given point in the object space is followed through the system, and the shape of the wave before and after each refraction is computed. Let V represent the optical distance from a given point source to any point in a given region. If V is known over any extended surface its value in the neighborhood of the surface is determined and the shapes of the wave fronts in the same region are also determined. The value of V over a spherical surface which osculates a wave front may be described in terms of a pair of polar variables forming a doubly infinite series with constant coefficients the values of which are directly related to aberrations present in the associated wave. Thus these coefficients may be used to describe the shape of the wave front. A straightforward although tedious derivation leads to formulae giving the coefficients of a refracted wave in terms of the coefficients of the incident wave.

11. Recent Developments in Refractometry. J. W. FORREST, *Bausch & Lomb Optical Company.*

Recent advances in oil technology have produced a method for the rapid and accurate evaluation of aromatic contaminants in hydrocarbon mixtures. This method involves the accurate measurement of the optical dispersion of the mixture. A refractometer has been designed which covers the required range (1.33–1.64) and has the precision and convenience necessary for this type of work. To overcome difficulties inherent in the use of a hydrogen discharge tube, the new instrument has been calibrated for a series of wave-lengths in addition to those of sodium and hydrogen and an illuminating device has been designed by which these sources can deliver monochromatic light to the refractometer. The problem of securing the individual lines of a source offers certain difficulties when the Abbé double prism is used, which are not present when only the second or measuring prism is used. The fields for various wave-lengths overlap in such a manner that it is necessary to add a dispersing member or an absorption filter in order to eliminate all wave-lengths greater than that producing the dividing line. With a mercury source this can be accomplished by filter, but with others the dispersing member produces the best results. The device consists of a slit, a collimating lens and a prism and gives excellent dividing lines even with a hydrogen discharge tube in which the residual bands due to oxygen are strong. A second development covers a small hand refractometer of unique design. The system is inverted with respect to standard types and operates only by reflection. The eye-point is just behind the prism, the dividing line being seen as a virtual image projected against a translucent scale. The scale and image are viewed simultaneously by

means of a specially corrected lens used as a simple magnifier. The border line secured in this manner is easily equivalent to that obtained by refraction through instruments of the standard type in which telescopes are used.

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"Quantitative determination of aromatic hydrocarbons by a new method," A. V. Grosse and R. C. Wackler, J. Ind. and Eng. Chem. Anal. Ed. (Nov. 15, 1939).
"Accuracy requirements in fifth place refractometry," H. W. Straat and J. W. Forrest, J. Opt. Soc. Am. 29, 240 (1939).

12. Brewsterian Angles and Refractive Index Measurements. A. H. PFUND, *Johns Hopkins University.*

An experimental procedure is described by means of which the Brewsterian angle may be determined with such precision that uncertainties of refractive index determinations lie in the third decimal place. The procedure outlined has two advantages: (1) it has no upper limit; (2) it is applicable to opaque as well as to transparent substances. Refractive index measurements of a variety of substances, including black glass, anthracite coal and amorphous selenium, are presented. Finally, the applicability of the procedure to the study of surface changes in refractive indices is discussed.

13. Metallic Mirrors and a New Gonioreflectometer. FRANK BENFORD AND W. A. RUGGLES, *General Electric Company.*

A study of the reflection characteristics of over a hundred mirrors of thirty-seven kinds has been made to get data that will permit both a comparison of mirrors and of the various methods and instruments for testing them. Tests were made of specular reflectance at angles from 15 degrees to 82.5 degrees and a new gonioreflectometer was built particularly for this work. The angular distribution data were used to compute average reflectances, and this was done in three different manners that represent three different points of view as to what average reflectance means. A number of alloys of aluminum were made and tested in an endeavor to improve over pure aluminum, and the entire group of mirrors was retested a number of times to determine the degree of permanence of the various metals.

14. The Performance of Optical Instruments with Coated Lens Systems. R. S. MORSE, J. E. TYLER, AND F. B. JEWETT, JR., *National Research Corporation.*

Coated lens systems show four important improvements in image-forming properties over identical non-coated lens systems: (1) Absence of flare images and flare marks, (2) increase in total light transmission, (3) increase of contrast in the image, (4) increase of detail in the image. These properties of coated lens systems are discussed and data are presented to illustrate the extent of the improvement.

15. An Optical Unit for Obtaining Variable Magnification. KENNETH N. OGLE, *Dartmouth Eye Institute, Dartmouth College.*

Research dealing with differences in the size of the ocular images of the two eyes demanded a means with which the size of the image of one eye could be varied continuously over a 5 percent range of magnification. Previously, a series of lenses in fixed steps of magnification was used. The solution to the problem was a two-lens plus-minus combination in which the axial separation could be varied mechanically. The most satisfactory system is obtained for units used in near vision (40 cm), where advantage is taken of the relationship between the conjugate distances and the lens power of a single lens when the longitudinal magnification is unity. The optical combination, as designed, provided a continuous range of magnification from -1 percent to $+5$ percent, with no measurable power error over that range. If the units were to have the same range of magnification for the distant (6-meter) vision tests as for the near vision tests, a power error which did not exceed ± 0.1 diopter could not be avoided. This error, however, is usually negligible in most visual tests. Units are made for over-all and meridional magnification. A description of the units themselves and of their optical properties is given.

16. Polarized Light Compensator for Vertical Illumination. J. R. BENFORD AND A. F. TURNER, *Bausch & Lomb Optical Company.*

The examination of opaque specimens in polarized light with the microscope using a vertical illuminator is usually of a qualitative nature. Berek[1] has shown that the usefulness of these polarized light methods in mineralogy and metallography may be extended by quantitative measurements of the ellipticity and of the rotation of the plane of polarization of the reflected light. These quantities are characteristic of the particular substance under observation and accordingly are helpful in the identification of an unknown. Compensators requiring a rotation of the analyzer as employed in the semi-aperture type of vertical illuminator cannot be used in conjunction with the full aperture polarizing vertical illuminator of calcite described by Foster.[2] In it polarizer and analyzer are combined and fixed in the crossed position. A compensator unit designed for this illuminator will be described. Compensation of rotation is obtained by the action of an interference film of high index material inclined to the optical axis and rotatable about it. Compensation of ellipticity is obtained with a thin mica plate covering the full aperture and rotatable in its own plane. Each of these elements is traversed by both the incident and reflected beams. From the extinction settings the rotation and ellipticity introduced by the specimen may be derived by reference to the Poincaré sphere.[3]

[1] M. Berek, Fortschritte d. Min. Krist. und Petro. **22**, 1 (1937).
[2] L. V. Foster, J. Opt. Soc. Am. **28**, 124 (1938).
[3] Cf. C. A. Skinner, J. Opt. Soc. Am. **10**, 491 (1925).

17. Absorption Cell for Long Optical Paths of Large Aperture. JOHN U. WHITE, *Esso Laboratories, Standard Oil Development Company.*

In the measurement of very weak absorption spectra on the vapor phase spectra of high-boiling liquids one must use either very long absorption cells or cells specially designed to give long optical paths by multiple reflections between the same mirrors. One of the latter type of absorption cell has been made that does not reduce the angular

aperture of the incident light beam either on or off the optical axis. Large apertures and high light transmission are obtained without the use of large mirrors. Three concave, spherical mirrors with the same radii of curvature are used, two at one end of the cell and the third at the other. The three are symmetrically arranged so that the third forms an image of each of the first two on the other. If, then, a light source is placed near one end of the third mirror, the first two form on the surface of the third a series of separate images, the last of which emerges beyond the other end of the mirror. Since a system of conjugate foci is established on the surfaces of the mirrors, no light is lost off their edges. With a source two centimeters long a transmission of 70 percent after eight traversals has been measured in the infra-red. Furthermore, the number of traversals can be varied at will by a simple adjustment. Diagrams and photographs will be shown.

18. Ultraviolet Irradiation by Means of Linear High Pressure Mercury Lamps. WM. T. ANDERSON, JR., *Hanovia Chemical & Mfg. Company, Newark.*

When the defense program began, manufacturers were confronted with the necessity for the reproduction of working drawings in very large quantity and at high speed. Manufacturers of reproduction equipment advised that existing light sources were not satisfactory, and requested the development of a linear high pressure quartz mercury arc lamp for the purpose. In accordance with this request, a number of such lamps have been developed which, as a result of their very high output in the near ultraviolet where diazo and other similarly treated papers have their maximum sensitivity, have been found suitable for use in high speed printers and in other photochemical processes. The optical requirements for the systems in which these linear lamps are used have been studied and are discussed.

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N. A. Halbertsma and G. P. Ittmann, Philips Tech. Rev. **4**, 181 (1939).
J. H. Laub, Elec. Eng. **60**, 384 (1941).

19. Rod and Cone Dark Adaptation: Surveys of Normal Subjects, and Applications to Clinical Problems. CHARLES SHEARD, *Division of Biophysical Research, The Mayo Foundation.*

The results of our tests on a large group of normal subjects will be presented to emphasize the importance of intensity, color, and duration of the preliminary exposure to light, the size and location of area of retinal stimulus, and the color of the stimulus in the determinations of rod and cone adaptation. To date, measurements of visual adaptation (both at the macula and in areas 5 or 10 degrees from the macula) and the courses of dark adaptation following exposure to 200, 500 and 1500 footcandles, respectively, for 4 minutes have been obtained on 75 pilots of a commercial air line, and on 110 school children. Another group of normal adults, ranging in age from twenty to sixty years, has been tested. These data have been examined statistically and the spread of 70 to 80 percent of the values of the dark adaptation levels at any given time of recovery has been determined. The effects on normal individuals of the intramuscular and the oral administration of large doses daily of vitamin A have been investigated. Methods and standards will be discussed and suggestions offered for the selection and rejection of candidates for special services. These findings on the dark adaptation levels for both cones and rods will be compared with the findings in certain pathological conditions, such as hyperkeratosis, vitamin A deficiency, and pityriasis rubra pilaris. As a whole, these investigations do not furnish evidence that there is any considerable part of the population suffering from vitamin A deficiency, and that, with visual adaptation within the normal range of expectancy, there is little or no effect of the administration of large amounts of vitamin A (e.g., 100,000 units) daily over a period of weeks on the dark adaptation levels.

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1. S. Hecht, and J. Mandelbaum, J. Am. Med. Assoc. **112**: 1910–1916 (1939). Also, Am. J. Physiol. **130**: 651–664 (1940).
2. L. F. Steffens, H. L. Bair, and Charles Sheard, Am. J. Ophth. **23**: 1325–1339 (1940).
3. G. Wald, H. Jeghers, and J. Armino, Am. J. Physiol. **123**: 732–746 (1938).

20. A Proposal for the Specification of Scotopic Luminosity. ELLIOT Q. ADAMS, *General Electric Company, Nela Park, Cleveland.*

The military need for "blackout" and blackout lighting has led to an increased interest in the specification of luminosity at low levels of illumination. In supplementing the data for the 1931 I.C.I. Standard Observer, it is desirable to observe the principles followed in the original specification: a considerable number of observers, avoidance of negative coefficients, and expression in terms of the equal-energy basic stimulus. Values of relative scotopic luminosity, $\bar{s}$, have been derived from the data of Weaver by normalization to equal area with the I.C.I. distribution coefficients, $\bar{x}$, $\bar{y}$, $\bar{z}$, and correction for residual cone vision.

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Licht u. Lampe **29**, 43 (1940); Rev. Sci. Inst. **7**, 322 (1936). D. B. Judd, J. Opt. Soc. Am. **23**, 359 (1933); K. S. Weaver, J. Opt. Soc. Am. **27**, 36 (1937).

21. Attributive Limens in Selected Regions of the Munsell Color Solid. BLANCHE R. BELLAMY, *Munsell Color Company,* AND SIDNEY M. NEWHALL, *Johns Hopkins University.*

Difference limens of hue, value, and chroma were separately secured at various representative locations in the surface color solid. There were three observers, each of whom furnished data for 150 limens. These limens were determined by an abbreviated form of the method of constant stimulus differences which gives the amount of difference in hue, value, or chroma great enough to be perceived in fifty percent of a number of separate trials. The observers were experienced and the conditions of viewing were highly favorable; consequently, the thresholds secured were presumably minimal. The mean of all hue limens was 0.50 hue steps, with a range of 0.05–1.40; the mean of the chroma limens was 0.25 chroma steps, with a range of 0.03–0.85; and the mean of the value limens was 0.021 value steps, with a range of 0.002–0.049. The detailed results are of interest in connection with such problems as

the setting of perceptual tolerances, the smoothing of the Munsell colors, and the equating of the attributive scales.

22. Adams' ICI $X-Z$ planes as they relate to studies of uniform chromaticity. DOROTHY NICKERSON, *Agricultural Marketing Service, U. S. Department of Agriculture.*

Last year Dr. E. Q. Adams described a new method of approach for plotting ICI tristimulus values, one that has many practical uses since it employs directly the ICI tristimulus values for a color. It eliminates the necessity for calculating trilinear coordinates; it refers surface colors directly to the illuminant for which they are calculated (not to the illuminant in terms of equal energy); it relates chromaticity differences after equating brightness (by plotting $X-Y$ against $Z-Y$, thus eliminating on a chromaticity diagram the Y value to which all the ICI luminosity is attached); and finally it succeeds, by a selection of appropriate scale factors, in producing as good a uniform chromaticity diagram directly from the use of ICI values as any other diagram yet seen. Of the three diagrams suggested by Dr. Adams' method of approach, (1) chromance, (2) chromaticity (as related to the chromance diagram), and (3) chromatic value, the last seems of the greatest interest and practical value since by its use the saturations of both light and dark colors will be plotted at more nearly the same point on the diagram. As demonstration, a series of diagrams will be shown. On each are plotted figures for the Glenn-Killian data for the Munsell color chips. These Munsell color chips are chosen for testing the relative adequacy of the methods of plotting because they are standardized, and represent the nearest thing to a psychologically equally-stepped series of scales for hue, lightness, and saturation that is available. If the Munsell colors are spaced as intended, then a plot of equal Munsell chromas for any given lightness (Munsell value) level will be a circle when plotted on a uniform-chromaticity-diagram, and if anyone should doubt that they are equally-spaced, the color chips themselves are available for observation in relation to the diagram one wishes to use. No uniform-chromaticity-diagram for practical work with surface colors should be accepted without an opportunity to look at the colors represented by points equally spaced on that diagram (although most of the work so far done in developing uniform chromaticity scales has been arrived at by observations and experiments with volume or film colors as seen in a photometric field). A series of diagrams representing Adams' chromatic value plots of the Munsell colors will be shown. They will include the smoothed chroma contours shown on ICI (x, y)-diagrams in Figs. 7–12 of the report by Dr. S. M. Newhall in the December, 1940, *Journal of the Optical Society of America.*

23. Photoelectric Colorimeter for the Grading of "Near White" Samples. ROBERT H. OSBORN, *Hercules Powder Company.*

In order to obtain ICI trichromatic coefficients from tristimulus colorimeters, three readings and a subsequent series of calculations must be made. In the routine grading of large numbers of samples, this process is often too time-consuming to be practical. A photoelectric colorimeter is described which may be used for the rapid and accurate chromaticity grading of "near white" yellow or blue samples. Essentially, the instrument consists of an optical system which provides illumination of the sample, two photo-cells, one of which views the illuminated sample through a violet glass filter, the other of which views the sample through a red glass filter, and an electrical measuring unit which measures the ratio of the responses of the two photo-cells. Each photo-cell views the same aspect of the sample by means of a 45-degree glass plate which transmits 92 percent of the light from the sample to one photo-cell and reflects 8 percent to the other cell. The responses of the two photo-cells were made approximately equal for a neutral gray sample by proper selection of the filters. The zero setting of the instrument is made with the aid of a ceramic standard. The extension of the principles of this instrument to the direct measurement of ICI trichromatic coefficients is discussed.

24. The Accurate Measurement of Specular Gloss. RICHARD S. HUNTER, *National Bureau of Standards.*

Specular gloss, defined as the ratio of the light flux specularly reflected by a surface to that incident upon it, is widely used for designating the gloss both of the non-metallic surfaces of paint, paper and like materials, and of metallic surfaces. To measure the specular gloss of typical surfaces provided for test, a device must respond to light reflected not only in the central direction of specular reflection, but in directions departing by small angles from this central direction. This leeway is necessary to accommodate light which departs from the axes of the incident and reflected beams because of (1) the non-flatness of the surfaces tested, (2) the finite size of the source, and (3) the possible aberration of the usual collimating lenses in the instrument. Assuming the spread[1] of the receptor to be greater than that of the source, the necessary leeway is provided in a specular gloss meter by the inclusion of two features: (1) a receptor collimator of greater aperture than the source collimator, and (2) a receptor focal-plane diaphragm with opening appreciably larger than the source. When any surface which does not reflect distinct images is measured in such a meter, the specular-gloss reading (G_s) is a function of the size of this receptor opening (s) as well as of the apparent reflectance of the surface (A) for the angular conditions of illuminating and viewing of the instrument:

$$G_s = \frac{s \cos \theta}{\pi f^2} A,$$

where θ is the angle of specular reflection and f is the focal length of the collimating lens. Thus the specular-gloss value assigned any surface not reflecting distinct images should always be accompanied by a designation of the solid angle of the receptor opening. In addition to showing the dependence of specular-gloss value on instrument aperture, the above relation is useful because it connects measured specular reflectance (G_s) and apparent reflectance (A) in which the light reflected by a surface is compared

with that reflected by the perfect diffuser. By inserting a value of A for a direction of diffuse reflection (such as $A_{45°,0°}$), the above equation may be used to compute the so-called diffuse correction for readings of specular gloss.

[1] R. S. Hunter and D. B. Judd, "Development of a method of classifying paints according to gloss," A.S.T.M. Bull. No. 97, 11 (March, 1939).

25. Measurement of the Accelerated Fading of Paints. A. J. EICKHOFF* AND R. S. HUNTER, *National Bureau of Standards.*

Two of the important evidences of the fading of paints, change of color and change of gloss, can be rapidly measured by photoelectric methods[1] developed within the past few years. Because ability to resist fading is a valued property of most paint and textile materials, improved methods for measuring the course of fading are in demand. Photoelectric tristimulus measurements of color change and photoelectric measurements of specular-gloss change were used to follow the fading of several paint samples exposed both outdoors and in two machines (A and B) designed to accelerate the weathering process. With these measurements it was possible numerically to compare the rates of artificial and natural fading of the paints. The data which were obtained showed: (1) Fading in machine A averaged 20 times as fast as fading outdoors, but it varied from roughly 5 times for one paint to roughly 40 times for another; (2) fading in machine B averaged 5 times as fast as fading outdoors, but it varied from roughly 3 times for one paint to 20 times for another, and (3) for almost every paint tested, the factor relating speed of fading in machine A to the speed outdoors was more nearly constant through the whole fading process than the corresponding factor for machine B. Thus machine A not only faded paints faster, but it provided a preview of the course of fading which was usually a better representation of outdoor fading than that provided by machine B. The data collected during the present study are noteworthy chiefly for the methods they demonstrate. These should be valuable for future studies of the fading of materials and for examinations of artificial methods for accelerating fading.

* Now with the U. S. Maritime Commission.

[1] R. S. Hunter, "A multipurpose photoelectric reflectometer," J. Research, Nat. Bur. Stand. **25**, 581 (1940) R.P. 1345; also J. Opt. Soc. Am. **30**, 536 (1940).

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